Exploring relevant technologies for simulating user interaction in Metaverse virtual spaces

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Abstract: The Metaverse concept describes a virtual collective space where users engage with simulated or computer-generated environments, enabled by cutting-edge technologies such as Virtual Reality (VR), Augmented Reality (AR), Blockchain, Artificial Intelligence (AI), and 5G Networks. This convergence allows the creation of complex virtual worlds, enhances user interactions, enables dynamic environments, facilitates seamless integration across platforms, and ensures scalability and persistence, alongside several privacy, security, ethical and legal challenges to be considered. The constant advancement of these technologies is pivotal in shaping a future where the line between physical and virtual realities blurs, unlocking limitless possibilities in realms such as communication, entertainment, education, and business. This leads to novel opportunities for exploration and user engagement. This paper aims to present an overview of the leading technologies driving the transition from the current Internet to the Metaverse, enabling users to interact naturally and intuitively with digital objects and environments. The study explores well-established interactive simulation technologies like virtual reality and augmented reality, along with emerging technologies like somato-sensory interfaces, holographic imaging, and brain-computer interaction interfaces. Emphasizing their potential, the paper demonstrates how these technologies can offer users unparalleled levels of involvement in interactive activities spanning gaming, socializing, education, and business.

Keywords: Metaverse, Virtual Reality, Augmented Reality, Blockchain, Artificial Intelligence, Immersive Experience.

Explorarea tehnologiilor relevante pentru simularea interacțiunii utilizatorului în spațiile virtuale Metavers

Rezumat: Conceptul Metaverse descrie un spațiu virtual colectiv în care utilizatorii interacționează cu medii simulate sau generate de calculator prin utilizarea unor tehnologii emergente, cum ar fi realitatea virtuală (VR), realitatea augmentată (AR), blockchain, inteligența artificială (AI) și rețele 5G. Această convergență permite generarea unor lumi virtuale complexe, îmbunătățirea interacțiunilor, facilitarea integrării multiplatformă, asigurarea scalabilității și persistenței, în paralel cu o serie de provocări legate de confidențialitate, securitate, principii etice și juridice care trebuie luate în considerare. Continua evoluție a acestor tehnologii reprezintă cheia către un viitor în care granițele dintre realitățile fizice și virtuale sunt estompate, fiind oferite posibilități nelimitate de transformare a multor domenii precum comunicarea, divertismentul, educația sau afacerile, creându-se astfel noi oportunități de explorare și implicare a utilizatorilor. Această lucrare își propune să prezinte starea actuală a principalelor tehnologii care conduc tranziția de la Internetul actual la Metaverse și care contribuie la simularea interacțiunii utilizatorului cu obiecte și medii digitale într-un mod natural și intuitiv. Prin urmare, vor fi examinate diverse tehnologii mature de simulare interactivă precum cele de realitate virtuală și realitate augmentată, dar și tehnologii emergente precum intrefețe somato-senzoriale, imagistică holografică și, mai nou, interfețele de interacțiune creier-calculator. Astfel, va fi subliniat potențialul acestora de a oferi utilizatorilor niveluri noi de implicare în activități interactive care includ jocuri, socializare, educație și afaceri.

Cuvinte cheie: Metaverse, realitate virtuală, realitate augmentată, blockchain, inteligență artificială, experiență imersivă.

1. Introduction

Currently, the ongoing transformation and advancement of the digital society have a primary objective: to recreate the physical world within the virtual space, ultimately enhancing the overall quality of life. This approach holds immense potential benefits, particularly in facilitating hybrid work models, widening access to education, ensuring easier access to information for citizens in matters of governance, fostering simpler and more satisfying social interactions, and promoting economic efficiency by eliminating unnecessary costs (Merezeanu et al., 2016). These possibilities

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hinge on the effective implementation of technologies equipment into daily routines, the development of high-speed networks and Web 3.0, advancements in artificial intelligence, the establishment of a robust IoT infrastructure, and the continuous improvement of Cloud infrastructure. Additionally, the success of this social innovation will be influenced by the degree to which users embrace and adopt digital assets and virtual experiences as part of their preferences. It is essential to note that these proposed mechanisms are designed to be user-friendly and unobtrusive, ensuring a seamless integration of technology into people's lives. At the core of these transformations lies the concept of the Metaverse, which encapsulates both the technological and social innovations.

The Metaverse introduces a revolutionary paradigm of a persistent, interconnected virtual world where individuals can work, socialize, and learn anytime, anywhere, and across various devices (Ning et al., 2023). Users can actively engage, either directly or through their digital avatars, utilizing a variety of devices such as glasses, smartphones, laptops, or headphones that facilitates participation in incredibly lifelike experience (Lee et al., 2021).

At present, several frequently used technologies, including virtual reality (VR), augmented reality (AR), and sensor-based technologies play vital roles in shaping and enhancing the immersive experiences within the virtual shared space. Augmented Reality and Virtual Reality serve as the gateway to the Metaverse, acting as powerful engines that support the creation of this immersive three-dimensional digital world, while sensor-based technologies have assumed a critical role in personalizing the Metaverse, by translating the received signals into the virtual environment.

Among the fundamental traits of the Metaverse, two stand out: its unrestricted and effortless access to resources and the potential for users to immerse themselves in captivating virtual experiences characterized by a high level of realism. To meet these demands, various technologies play a crucial role in enabling access to the virtual environment. This article reviews the main user interaction technologies that not only facilitate access but also enhance the creation of immersive experiences within the Metaverse. The contribution of this article can be summarized as follows:

a) A new framework is proposed for the primary key aspects of the Metaverse, facilitating the modeling of its evolution and offering essential guidance in designing virtual environments and the corresponding supporting technologies.
b) A new perspective on the structure of technological clusters is introduced, which constitute the foundational elements of Metaverse development, with a particular focus on their convergence and user engagement.
c) Through an examination of present-day technologies relevant to simulating user interaction in the Metaverse, including VR, AR, and others technologies, this article emphasizes the gap between user expectations, the fundamental demands of the Metaverse, and the capabilities provided by the existing state of technological advancement.

This article attempts to offer a comprehensive outlook on the main technologies concerning User Interaction in Virtual Spaces, being structured as follows: Section 2 outlines the key characteristics of the Metaverse, providing guidance for designing virtual environments and the supporting technologies. The technology clusters forming the foundation for Metaverse components and related experiences are also discussed, with a particular emphasis on convergence and user engagement. In Section 3, the main technologies within the cluster dedicated to user interaction simulation in the Metaverse are presented. Section 4 builds upon the insights drawn from the preceding analyses to address various challenges within the Metaverse, shedding light on the gap between expectations and the current state of their development. Lastly, the conclusions of this article outline potential avenues for future research and work.

2. Metaverse technological convergence: empowering the user experience

2.1. The main characteristics of the Metaverse

The characteristics of the Metaverse encompass the fundamental elements that define this concept, serving as a blueprint for its evolution and providing direction for designing virtual environments and the supporting technologies. For instance, its immersiveness feature dictates the extent of realism and interaction, while the shared virtual environment highlights the significance of social engagement and collaboration, crucial for fostering a sense of community within the virtual realm. Additional aspects, like content generation, empower users with creative control over their virtual experiences, and interoperability ensures a seamless and interconnected virtual world (ENDERS Analysis, 2022). Other features, such as decentralization, economics, accessibility, privacy, and security, contribute to shaping the overall vision and goals of the Metaverse. These characteristics establish a framework of values and principles that lead to Metaverse development, ensuring it remains a safe, interconnected, and engaging environment for all users.

At present, there is no standardized framework that offers a comprehensive and universally agreed-upon representation of the fundamental features and attributes that define the virtual, interconnected universe. According to Deloitte, (2022) there are six key characteristics that describe the Metaverse, namely: Immersive Experience, Complete World System, User-Generated Content, Huge Economic Value, New Regulation, Big Uncertainty. Another approach is offered by Sun et al., (2022) which summarizes the characteristics of the Metaverse in three major categories: spatio-temporal extensibility, virtual-real interaction, and human-Computer symbiosis, while Wang et al., (2022) specify unique features of the Metaverse from the following perspectives: Immersivenes, Hyper Spatiotemporality, Sustainability, Interoperability, Scalability, Heterogeneity.

While these approaches provide a general understanding of the fundamental Metaverse characteristics, it is important to acknowledge that the concept is still emerging and the associated technologies are not fully developed. As a result, there is a need for an extended framework that represents the primary Metaverse characteristics comprehensively. In this context, a more inclusive approach will be proposed that organizes the main Metaverse characteristics into four categories as presented in Figure 1: time-space permeability, real-virtual mirroring, multi-technological convergence, and human-computer connection. This comprehensive framework presented in figure1 aims to encompass the essential elements that define the Metaverse, considering its dynamic and evolving nature.

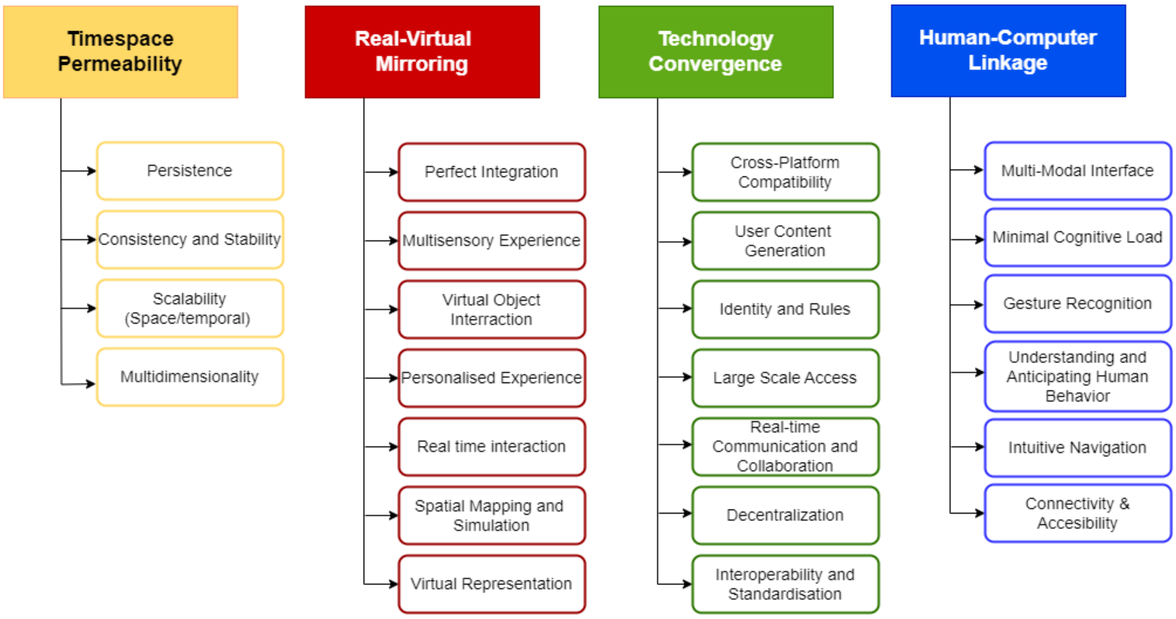

Figure 1. Key characteristics of Metaverse

2.1.1. Time-space permeability

Time-space permeability is a critical characteristic of the Metaverse, allowing users to interact and navigate seamlessly across virtual environments with different timeframes and spatial scales (Sun et al., 2022). Essentially, the Metaverse serves as a virtual extension of the real-world space inhabited by humans, where real and virtual spaces are interconnected and mutually influential. Unlike the finite constraints of real space, the space in the Metaverse is boundless, offering infinite possibilities. The main characteristics in this category are as follows:

- *Persistence*: ensure that changes made to the virtual environment endure over time, even after users log out. This feature is achieved through the implementation of distributed networks, where data is stored across multiple servers and devices, and by leveraging blockchain technology, which guarantees secure and decentralized data storage.
- *Consistency and stability*: are two essential features of the Metaverse, ensuring a continuous and secure user experience. Several key factors including performance, uptime, decentralized regulation, and security contribute to maintain consistency and stability in the Metaverse. To achieve stability, the Metaverse must also be adaptable to evolving user needs and technological advancements.
- *Scalability*: in the context of the Metaverse, scalability is a factor that characterizes three main attributes of the Metaverse: infrastructure, space, and time. At the infrastructure level, the Metaverse must ensure the necessary capacity to handle an increasing number of users, objects, and interactions without sacrificing performance, quality, or accessibility. If in the real world the space is quantifiable and finite, in the virtual world it can be extended, the only barrier being the resources and infrastructure allocated to this operation. Unlike to the linear progression of time in nature, the Metaverse operates with a retroactive time concept, allowing access sequentially to the past, present, and future.
- *Multidimensionality*: this feature addresses several aspects that contribute to the creation of attractive digital experiences for users that can be modeled and explored in various ways. The Metaverse exhibits multidimensionality primarily through five key aspects: the spatial dimension, the functional dimension, the personal dimension, the creative dimension, and the technological dimension.

2.1.2. Real-virtual mirroring

This category refers to the concept of synchronizing and reflecting real-world elements and behaviors within the virtual environment of the Metaverse. It involves creating a close correspondence between the physical world and the virtual world, blurring the lines between the two. Here are some key characteristics associated with real-virtual mirroring in the Metaverse:

- *Perfect integration*: although conceptually similar, this characteristic can be applied in two directions of Metaverse development: a) integration between the real world and the Metaverse; b) integration between different virtual worlds/spaces within the Metaverse without barriers or limitations. To achieve true seamless integration, the following key elements will need to be considered: connectivity, interoperability, security, privacy, and user-friendly interfaces.

- *Real-Time Interactions*: actions and behaviors within the Metaverse can be closely linked to real-world counterparts. For example, physical movements captured by motion-tracking devices can be translated into corresponding avatar movements in real-time.

- *Spatial Mapping and Simulation*: real-world environments can be scanned, mapped, and replicated in the virtual space, allowing users to interact with real-word locations, landscapes, architecture, and even weather conditions in the Metaverse.

- *Virtual Object Interactions*: users can manipulate virtual objects, and the corresponding real-world interactions or movements can be translated into the virtual space, allowing for intuitive and natural interactions.

- *Virtual Representation:* users have virtual avatars that mirror their real-world appearance or can be customized to reflect their desired identity, providing a sense of personal connection and familiarity.

- *Multi-Sensory Experience*: a multi-sensory experience in the Metaverse involves engaging multiple senses simultaneously, such as sight, sound, touch, and, in some cases, smell or taste. Current commercial extended reality (XR) platforms predominantly focus on visual and auditory elements, with limited haptic feedback. However, emerging platforms are incorporating sensing and synthesis capabilities to extend the Metaverse to encompass the entire range of human senses, including detailed touch, temperature, smell, and taste.

- *Personalized Experience*: experiences within the Metaverse are custom-tailored to each individual user, considering their preferences, behavior, and historical interactions, resulting in highly personalized and captivating interactions.

2.1.3. Technology convergence

The Metaverse achieves a seamless integration of the real and virtual worlds by harnessing a diverse range of emerging technologies, thereby providing users with immersive and interconnected experiences (Wang et al., 2022). This integration is made possible through the convergence of various technologies, such as virtual reality (VR), augmented reality (AR), artificial intelligence (AI), blockchain, and others. These technologies work together to create novel forms of social interaction and personalized experiences. For instance, users in the Metaverse can employ VR technology to completely immerse themselves in virtual environments, while AI technology facilitates intelligent and tailored interactions with virtual objects and other users. Additionally, blockchain technology plays a pivotal role in establishing a secure and decentralized economy within the Metaverse, enabling users to buy and sell virtual goods and services (Park & Kim, 2022). The convergence of technologies in Metaverse can be highlighted in the following points:

- *Cross-Platform Compatibility:* the Metaverse is designed to be accessible across multiple platforms and devices, allowing users to engage with the virtual world using their preferred technology.
- *User Content Generation:* unlike traditional internet platforms, where owners primarily generate content and enforce rules, in the Metaverse, users take charge of content creation and rule-setting. The platforms, instead, furnish users with the necessary technical tools to design and shape their virtual objects, environments, and experiences.
- *Identity and Rules:* this characteristic pertains to how virtual identities are managed and how rules and regulations govern user behavior and interactions within the virtual world. This characteristic involves several key aspects: digital identity, identity verification rules and governance, moderation and content guidelines, privacy, and data protection etc.
- *Large Scale Access:* this feature aims to promote broad and inclusive participation within the Metaverse, ensuring that the advantages of the virtual world are accessible to as many individuals as possible, regardless of their background, abilities, or identities.
- *Real Time Communication and Collaboration*: the Metaverse integrates various communication technologies like voice chat, video conferencing, and messaging to facilitate real-time interaction and collaboration among users.
- *Decentralization*: this feature entails distributing decision-making authority across a network of nodes rather than being concentrated in a single entity or authority. In a decentralized Metaverse, users have the autonomy to determine how they interact with the environment and each other. They can create their own content, establish rules and regulations, and even participate in the governance of the Metaverse. However, building a decentralized Metaverse presents challenges, including technical obstacles and the need for effective governance structures that accommodate diverse stakeholders' interests. To address these challenges and ensure the coherence of virtual spaces, rules and standards may be implemented through decentralized autonomous organizations (DAOs).
- *Interoperability and standardization*: These features are vital for the advancement and expansion of the Metaverse. As a virtual realm connecting diverse environments and experiences, interoperability enables smooth navigation between different spaces.

2.1.4. Human – Computer linkage

To achieve human-computer linkage in the Metaverse, several aspects are crucial. Firstly, computing machines need to be capable of real-time thought processes aligned with human thinking, complementing human capabilities to reach optimal solutions. New sensory perception and AI technologies support more natural and intelligent human-computer interactions while multimodal interaction, utilizing keyboard, mouse, voice, expressions, and gestures, enhances UX. Some of the main feature in this category include:

- *Multi Modal Interface*: Combining multiple modes of interaction, such as touch, voice, and gestures, offers users diverse and flexible ways to engage with the virtual environment.
- *Gesture Recognition:* Advanced gesture recognition technology enables users to interact with the Metaverse using natural hand movements, enhancing immersion and ease of use.
- *Minimal Cognitive Load*: The interface design should minimize cognitive load and distractions, allowing users to focus on their activities and experiences within the Metaverse.
- *Understanding and anticipating human behavior*: In both social environments and the Metaverse, comprehending and predicting human behavior is crucial for crafting a more personalized, engaging, and enjoyable virtual experiences for users. To achieve this feature, several technologies and methodologies are necessaries: Data Analytics, Artificial Intelligence (AI) and Machine Learning, Emotion Recognition, Predictive Modeling, Social Interaction Analysis, Context-Aware Experiences, User Feedback and Surveys etc.
- *Intuitive Navigation*: the interface should be intuitive and easy to use, allowing users to navigate the virtual world effortlessly using familiar gestures or controls.
- *Connectivity and Accessibility*: this characteristic relates to users' ability to access the virtual world, regardless of the devices they use. It encompasses the capability to interact with virtual environments, objects, and other users, along with real-time communication. Ensuring the necessary level of connectivity for the Metaverse requires a combination of technologies and infrastructure components, such as high-speed Internet connections, low-latency network infrastructure, and robust computing and storage capabilities. The interface with the virtual world should include accessibility features, making the Metaverse experience inclusive and accommodating for users with disabilities.

2.2. Integrating technologies into the Metaverse

To achieve interconnected virtual environments that offer immersive experiences to users, a high degree of convergence or integration among the core technologies supporting the development of the Metaverse is necessary. This convergence empowers the creation of sophisticated and realistic virtual worlds, where users can engage in diverse activities, such as gaming, socializing, conducting economic transactions, and even participating in educational processes (Ball, 2022).

In Figure 2 are the main groups of technologies that underlie the realization of the Metaverse components and associated experiences. Each group is composed of several subcategories, each of these subcategories having the ability to support multiple Metaverse features. The main groups (clusters) of technologies in correspondence with one or more features of the Metaverse are: *User interaction simulation technologies, Artificial intelligence, Decentralized technologies (Blockchain), Content creation and spatial computing technologies, Data transmission technologies and network edge computing.*

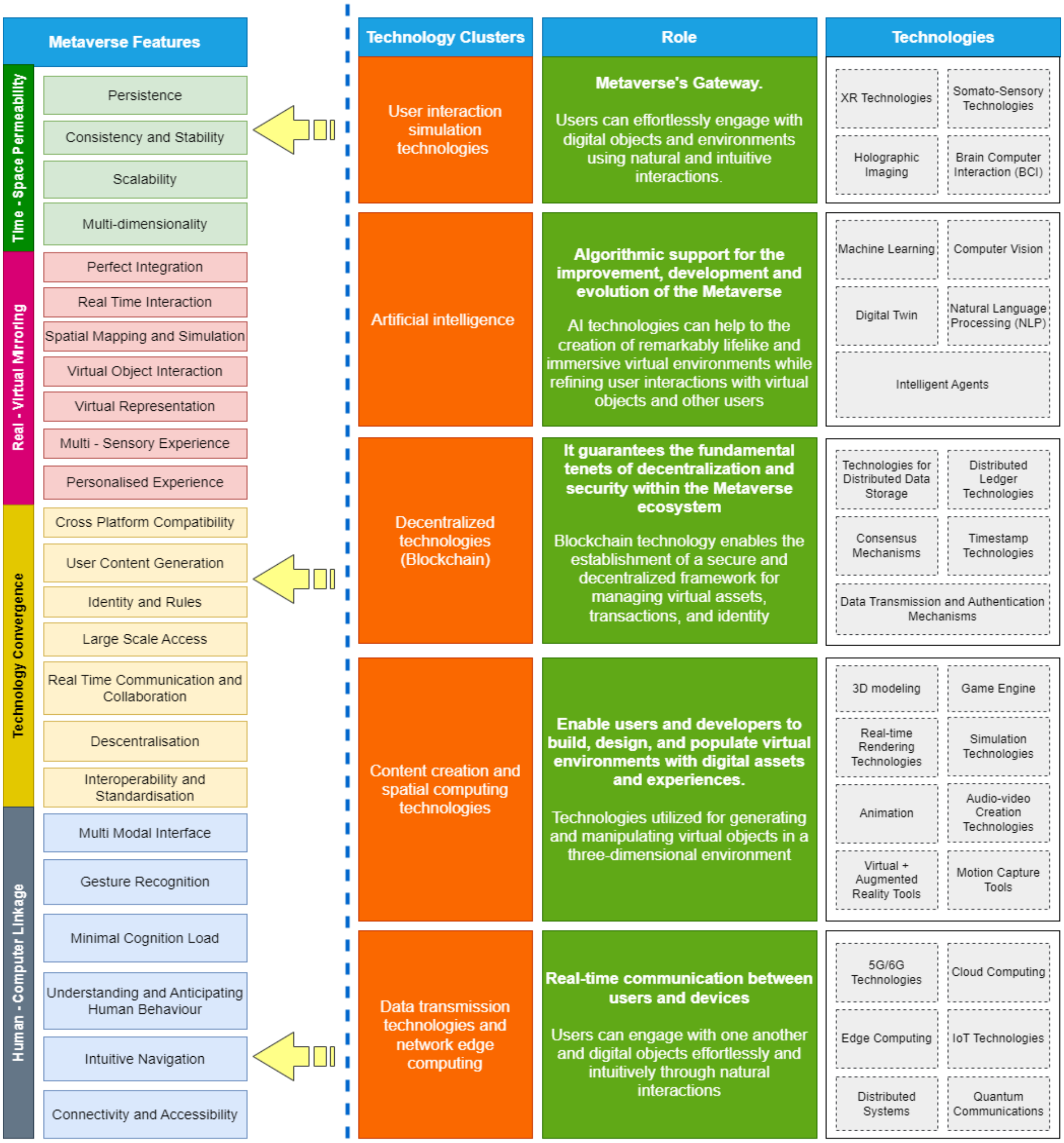

Figure 2. The main groups of technologies supporting Metaverse

3. User interaction simulation technologies

In the Metaverse, user interaction simulation technologies play a vital role in crafting captivating experiences. This cluster of technologies primarily encompass technologies that facilitate user immersion in virtual environments. Innovative technologies in various stages of development and testing, including Virtual Reality (VR), Augmented Reality (AR), haptic feedback, holographic images, human-computer interfaces, and more advanced forms of technology like Machine Learning (ML), computer vision, speech recognition, and Neuro-linguistic programming (NLP) are poised to revolutionize the creation of sensory experiences (Reiners et al., 2021). Technology convergence will empower users to interact with one another and their virtual environment in a remarkably natural and intuitive manner. Such advancements will offer an extensive array of experiences and opportunities, profoundly impacting human society from a socio-economic standpoint. As this technology-driven evolution unfolds, the Metaverse is set to redefine how to connect, communicate, and engage with one another, blurring the boundaries between physical and digital realms (McKinsey & Company, 2022).

3.1. XR Technologies

With the achievement of a high level of sensor miniaturization and the maturation of technologies (hardware and software) integrated into various devices and systems, a new family of technologies has been developed that allow immersion in the virtual environment, called Extended Reality - XR.

Extended Reality (XR) refers to a family of technologies that combine real and virtual environments to create immersive experiences for users. XR includes virtual reality (VR), augmented reality (AR), and mixed reality (MR). As miniaturized sensors and embedded technology mature, it is predicted that XR devices such as head-mounted displays (HMDs) will become the primary means of accessing the Metaverse. Equipped with fine human-specific information perception and ubiquitous sensors, XR wearables can detect and respond to objects and surroundings, assisted by smart indoor devices such as cameras. This means that user/avatar interactivity will no longer be restricted to mobile inputs such as phones and laptops, but will be available through a wide range of interactive devices connected to Metaverse. XR aims to provide an all-encompassing experience that immerses users by stimulating their sight, hearing and touch to facilitate input and output of information in Metaverse using motion tracking technology. The most advanced virtual space technology currently involves visual and auditory simulation interaction in somato-sensory realization. Although attempts have been made to simulate human smell, touch and thought, they are not as developed as visual and auditory simulations.

3.1.1. Augmented Reality (AR)

Augmented reality (AR) is a technology that superimposes computer-generated information on real-time images of the surrounding reality, the result being a reality supplemented with virtual information. Real-world images can be captured optically or via a video camera, the latter being the most widespread mode today. Display devices can be monitors, mobile device screens, or head mounted devices.

A comprehensive definition of augmented reality is made by Azuma (1997), who considers it to be a variation of virtual environments or virtual reality. While virtual reality involves total immersion of the user in the synthetic environment, without him having the possibility to see the real world around him, augmented reality allows the user to see the real world, with virtual objects superimposed or supplemented with real objects. Thus, augmented reality supplements reality rather than replacing it completely. At the mental level, real and virtual objects will appear to the user as coexisting in the same space. Technologies based on augmented reality have a wide applicability, especially in the educational field due to facilitating the understanding of knowledge and increasing the motivation of students (Alotaibi, 2023; Iordache, 2015).

Generating an augmented scene requires merging a real image with computer-generated graphics through a system that requires a video camera connected to a computer or mobile device. The purpose of the video camera is to capture the scene – the actual image – that is to be augmented. The position of the video camera is known to the computer and is represented by means of a coordinate system. For the positions of the real images to be aligned with those of the virtual images, a coordination of the two coordinate systems corresponding to the real camera and the virtual one is necessary. Once the computer graphics are generated, one can proceed to the last step: superimposing the virtual image over the real image. There are two main technologies through which scene visualization can be achieved: Head Mounted Display (HMD) and Video Screen Interface.

3.1.2. Virtual Reality (VR)

Virtual Reality (VR) represents a set of technologies that allow a person to interface with an artificially created environment. The defining concepts for virtual reality are: immersion, simulation, three-dimensional environment, interaction, avatar; synthetic medium, telepresence. Immersion is a key element in VR systems, being a state in which the awareness of one's own person is diminished or lost by entering a totally immersive environment, often artificial. This state of mind is frequently accompanied by an excessive spatial sense, intense focus, a distorted sense of time and effortless actions.

Being a complex hardware-software system, with strong psychological and cognitive implications, there are numerous definitions in the literature that emphasize these different aspects. Thus, Vlada & Popovici (2004) state that "in virtual reality, the computer and specialized equipment change the way humans perceive reality in the natural environment, by simulating/modeling another reality". Moldoveanu et al. (2009) consider that a virtual reality application (3D virtual space) is a software application that combines informational elements and rich and complex user interactions, the definition being the attempt to immerse in a world represented with the help of advanced 3D graphic elements. Craig, Sherman & Will (2009) define VR as a "simulation of an environment that allows a person to experience places and actions other than those in reality or inaccessible in reality".

It can be concluded that virtual reality can be defined as a category of multisensory communication technologies controlled by computer or mobile devices, which allow more intuitive interactions with data and involve human senses in new ways. What differentiates VR from other types of computer applications is the sense of presence or immersion. VR implies a much higher degree of interactivity than in traditional multimedia applications.

3.1.3. Mixed Reality (MR)

The term mixed reality was introduced by (Milgram & Kishino 1994) and encompasses those technologies that combine the characteristics of virtual reality with those of augmented reality. MR integrates virtual objects into the real world and allows the user to interact with the objects, producing new environments where physical and virtual elements coexist and interact in real time. Mixed reality allows users to navigate both the virtual world and the real world at the same time. Virtual elements are superimposed on the real environment, making interactions with these objects appear real. Mixed reality offers experiences in the virtual world in a more dynamic and natural way and makes experiences previously impossible in the real world possible.

3.2. Somato-Sensory Technologies

These technologies aim to capture and simulate sensory inputs related to touch, feel, and bodily sensations to enhance the user's sense of presence and immersion. Some relevant somato-sensory technologies that could be integrated into the Metaverse include: Haptic Feedback Devices, Full-Body Motion Capture, Tactile Suits, Olfactory Interfaces, AR&VR technologies.

3.3. Holographic Imaging

Holographic imaging is a method of recording a three-dimensional image on a generally two-dimensional support, the recordings obtained being called holograms. The same method can be applied to the recording, playback, and processing of data other than visual. Thus, the holographic image is the result of the combination of computer technology and imaging technology, and uses the coherent interference of light to record the amplitude and phase information of the light wave and obtain all the information about the object, including the shape, size, etc. The holographic image is a real three-dimensional image. Users can view the image with the naked eyes at different angles without wearing hand-held devices. With the development of technology, the boundary between the physical world and the virtual world can be blurred, which will create a solid foundation for the real realization of the Metaverse.

Ramesh et al. (2022) created a holographic environment of various human anatomical structures, such as the eyeball, cerebral venous system, cerebral arterial system, cranial nerves, and different parts of the brain to serve as pedagogical and counseling tool for learning through game and for counseling. He et al. (2023) proposes a real-time three-dimensional communication system that integrates hologram capture, generation, transmission, and display as a potential solution for telepresence in the Metaverse.

The main technologies and areas of applicability regarding holographic imaging refer to:

- Synthetic Reality (Synthetic Reality): refers to an advanced form of virtual reality in which the computer (or virtual) world can anticipate a user's actions and/or inputs and adjust accordingly to generate the best possible results.
- Hyper realistic Representations of Human Bodies: mimics the shape, contours and textures of the human body or its parts, producing a convincing body illusion. The accuracy with which the details of the body are reproduced creates the feeling that you are in the presence of an exact replica of figurative reality.
- 3D Holograms: A 3D hologram is a 3D projection created by the refraction of light floating in space. Unlike 3D TVs, virtual reality (VR) or augmented reality (AR) applications, 3D holograms can be viewed by anyone without additional devices.
- Tensor Holography: The Massachusetts Institute of Technology (MIT) published research in 2021 that demonstrates a new method of generating holograms using artificial intelligence to create real-time holographic content. This new method is called Tensor holography and can run on smart devices like phones or laptops.

3.4. Brain-Computer Interfaces (BCI)

Brain-Computer Interfaces (BCIs) are those systems that provide a direct connection between the brain and the computer to control an external device. These interfaces encode and decodes brain signals in the process of brain activity by accurately identifying brain signals, which can be used by users for activities such as gaming, typing, etc. BCI connects the human neural world with the external physical world by decoding individual brain signals into commands recognized by computing devices, which can achieve the spatial convergence of the virtual world and the real world. Currently, there is also research on BCI based on AI technologies (Aggarwal & Chugh 2019; Fahimi et al., 2020; Zhang et al., 2019) to accelerate the development of BCI and lay the foundation for the space convergence of the Metaverse.

In the specialized literature, BCI systems are defined as systems that measure the activity of the central nervous system of the brain and transform it into an artificial output, thus ensuring the interaction between the central nervous system and its internal and external environment (Wolpaw, 2012). A modern BCI system involves analyzing brain activity that takes complex brain signals and translates them into commands for a device (typically a computer, a robotic arm, game controllers, prosthesis, wheelchair etc.) (Özbeyaz, 2021).

Depending on the method of signal acquisition (Rosenfeld & Wong, 2017), a distinction can be made between:

- Invasive BCI technologies - use arrays of electrodes implanted in the human cortex to actuate cortical neuroprostheses and allow users to regain limited control over their environment (Klaes, 2018);
- Non-invasive BCI technologies - use EEG signals from electrodes placed on the scalp;
- Hybrid BCI technologies – combine invasive and non-invasive modalities to improve classification accuracy and reduce signal detection time.

Unlike non-invasive BCIs, the great opportunity offered by invasive BCIs lies in precise control, a prerequisite being user acceptance, combined with the restoration of somato-sensation. User acceptance is lower for invasive than noninvasive BCIs (Blabe et al., 2015). Invasive BCIs are usually used in patients either for research purposes. Current commercial BCIs are mostly non-invasive. This lower acceptance arises mainly from medical concerns about neurosurgery and the implant. Such risks are clearly not negligible, but appear to be partly overestimated.

4. Challenges and expectation

To ensure user satisfaction, the Metaverse must be operated with a strong emphasis on meeting their needs. This requires the development of resilient technologies capable of supporting the Metaverse's expansion over the long term. Essential principles of the Metaverse encompass criteria such as adhering to standards and interoperability, achieving scalability, and establishing a reliable underlying infrastructure that can handle the requirements of all significant users and content creators (Corretge, 2022).

The current stage of Metaverse technologies indicates that they are still in their early development phases, with diverse approaches being explored in various projects. However, some technologies require an advanced level of implementation, while other components are still in need of creation and development (EU Council, 2022). These include aspects such as User experience (UX), Human Machine Interface (HMI), and a sophisticated telecommunications infrastructure.

Challenges derived from the current development of the Metaverse are diverse and multi-faceted. As this concept continues to evolve, several challenges need to be addressed, and certain expectations arise from its development. The idea of being part of a fully immersive, interconnected digital world where users can interact with each other, create content, and experience virtual reality environments, can become extremely attractive for many people. Therefore, users imagine the Metaverse as highly realistic, intuitive, and accessible, offering a wide range of experiences similar to or even surpassing real life. This expectation is based on the constant advance of various virtual reality technologies such as AR, VR, MR, but currently, no single platform or technology has achieved the level of sophistication and integration needed to create a fully realized Metaverse. Many existing platforms are still limited in scope and functionality, and there are challenges in terms of hardware requirements, user interface, content creation, and network infrastructure (AL Otaibi et al., 2023). Issues like visual fidelity, haptic feedback, and locomotion in VR remain areas of ongoing research and development.

Users expect to seamlessly transition between different experiences and maintain a consistent identity and assets across platforms. Unfortunately, there are a multitude of standards and protocols governing cross-platform interactions, making full Metaverse-level integration difficult (De Giovanni, 2023). Other concerns refer to the digital divide, as not everyone has access to the required hardware and high-speed internet needed for a satisfactory Metaverse, and implicitly regarding the degree of the availability of diverse and engaging content. Moderation, copyright issues, and ensuring a safe environment for all users represent technological challenges that must be overcome for a successful Metaverse. This is not possible without ensuring solid confidentiality and security measures regarding personal data and information.

5. Conclusions and future directions

In general, the technological infrastructure of the Metaverse entails considerable expenses, requiring substantial effort, resources, and education. However, there are cases where Metaverse does not meet users' expectations. For example, current VR headsets may lack optimal sensitivity, and the process of adapting the body to simulated environments raises potential health and safety issues. Nonetheless, the immense potential of the Metaverse in various domains remains intact, and emerging technologies with longer adaptability times continue to contribute to its advancement.

The technologies driving user interactions within the Metaverse play a vital role in its growth and evolution, especially in crafting immersive user experiences. These technologies empower the creation of realistic virtual environments, enhance interactions, generate dynamic worlds, enable seamless cross-platform integration, ensure scalability, and maintain persistence. However, they also lead to various challenges related to privacy, security, ethics, and legal considerations that must be addressed. By combining VR, AR, haptic feedback, NLP, and ML technologies, the Metaverse is poised to become a virtual realm where users can naturally and intuitively engage, offering a wide range of experiences and opportunities.

The integration of these technologies has the potential to elevate the Metaverse experience, offering users novel and unparalleled ways to interact with virtual environments. As researchers and users increasingly focus on the possibilities of Metaverse technology and related disciplines, exploration of applications in various fields is encouraged. Nevertheless, this exploration also rises challenges and issues that developers and users alike must address and overcome.

The Metaverse can be envisioned as a fully immersive virtual space merging the physical and digital worlds, integrating emerging technologies like Digital Twins (DT) that mirror digital objects in the real world, VR and augmented reality (AR) providing immersive 3D experiences, wearable sensors, and brain-computer interface (BCI) systems facilitating user/avatar interaction, as well as AI, blockchain technology and non-fungible tokens (NFTs) playing crucial roles in intellectual property rights management within the Metaverse. Such convergence offers exciting research opportunities that can be realized through focused research activities, leading to improvements in Metaverse-specific artificial intelligence models and algorithms, disseminated through conference papers and specialized journals.

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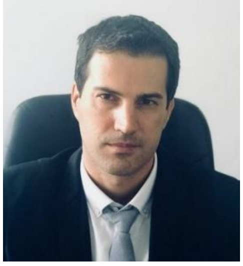

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