

Enhancing the Metaverse: Integrating IoT Devices to Elevate User Experience

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Abstract:

This paper explores the integration of IoT devices in the Metaverse to enhance the user experience. This study aims to provide insights into optimizing user interaction within virtual environments by examining design considerations, challenges, and potential solutions. The findings highlight the significance of seamless and immersive experiences, addressing latency, security, and interoperability issues. Here, they focus on features such as “ease of use,” “customizable and friendly” user interfaces, and “interactivity” as opportunities; “latency” and “security risks” as threats. We present possible resolutions such as edge computing, analytics tools, and several security measures to respond to these threats. This paper aims to investigate how the use of IoT devices influences the Metaverse from the user’s perspective and how designers can enhance it accordingly. The proposed solutions include the following: introducing several measures to optimize the use of IoT devices in the Metaverse design and tempering with the Metaverse design to create a more engaging, safe, and secure environment for the user. Future research directions are also suggested to improve the integration of the IoT in the Metaverse.

Keywords: Metaverse, IOT, User Experience, IoT Challenges, Virtual Reality, Metaverse Architecture, Metaverse Components

1. Introduction

The metaverse is a term used to describe worlds that appear to be created through a combination of physical and virtual objects. Integrating IoT technology into the system will give users more data more control over their experience and better access to the Metaverse. The Internet of Things (IoT) has had a profound impact on the user experience because the advancement of sensors allows users to access real-time data, receive targeted notifications and alerts, and manage complex systems from a single connected device. This allows designers to be capable of creating immersive and engaging experiences that were previously impossible, improving the overall user experience.

The development of open surroundings that hyperlink 3-D virtual worlds with IoT-enabled bodily environments is made possible through the Metaverse. This gives users immersive reports that mix the virtual and physical worlds. The Metaverse is predicted to permit customers to interact with digital items and environments in actual time, allowing a continuing transition between the bodily and digital geographical regions. By developing a regular and protected network, Metaverse aims to offer customers new degrees of immersion, interactivity, and engagement both digitally and physically (Li et al., 2022).

According to forecasts released through Bloomberg, Metaverse is expected to develop an enormous market that will reach a valuation of \$800 billion by 2024. This incremental growth is driven by the increased allocation of time in the virtual realms and connected online communities. Insights from Accenture's Technology Vision 2022 illustrate that 71% of global corporate executives see it as aligned with their strategic business plans, and approximately 40% of CEOs see it as transformational (Rishi Mohan Bhatnagar, 2022).

The metaverse can leverage the Internet of Things (IoT) to offer users seamless and completely immersive experiences online. It does this by translating live IoT data from the physical world into the Metaverse reality. This approach makes the virtual experience of users more realistic and enhanced by integrating real-world data via the IoT, making its interface much more interactive. This can be achieved with augmented reality (AR) and virtual reality (VR) technologies, which can create a more immersive and engaging experience for users (Pereira et al., 2021).

2. Motivation

The inclusion of IoT devices within the Metaverse is one of the emerging trends within the latest developments, with the potential to contribute to changes in user experiences. With the increase in popularity of the Metaverse, the combination of reality brings improved levels of interaction with the data and control over the data, providing the users with a higher level of reality. However, the integration of both loops is not without its problems.

Nonetheless, there exist some significant challenges that need to be considered to harness the true potential of the IoT in the current trend of the Metaverse. Some of the challenges are related to the latency and response times of the underlying messaging platforms, security, privacy, preserving data integrity, and compatibility of different devices and operating systems. These factors underscore the importance of establishing strong and viable solutions to build a good and rational

user experience.

To solve these challenges, new concepts such as, for example, edge computing, better analytical instruments, and primarily secure solutions must be used. The use of edge computing mitigates the problem of latency to the extent that the data can be processed closer to the place where the likely interactions may occur online. The application of the analytical tools is useful when trying to understand the client and his/her choice, and this will assist in developing a better virtual environment. Considering the sensitivity of data that could be submitted to the Metaverse by users, protection is required to guarantee that such information would not be captured by a third party; otherwise, this would defeat the purpose of a customer visiting the Metaverse.

Therefore, in the framework of preparing this paper, the following structure is proposed: first, the application of Metaverse in different industries to underscore the need for the integration of the IoT with the Metaverse; second, the issues arising from IoT integration with the Metaverse are explored. We also elaborate on potential solutions to these challenges and explain how they will assist in enhancing the user interface. The following section presents the literature review and discussion on IoT applications in Metaverse divided across several industries before its extension in other sections of the paper. Therefore, it is possible to define solutions for these elements and develop a set of guidelines for achieving such objectives to ensure the successful inclusion of IoT devices in the Metaverse at the dawn of the new period of connected and Evolutionary digital environments.

3. Literature Review

This chapter focuses on a study of different industries from the perspective of the metaverse and IOTs and the critical components of the metaverse in the context of the user experience.

3.1 The Metaverse: Changing Industries through IoT Integration

The integration of IOTs and Metaverse will help transform various industries by providing seamless and immersive experiences to the user. Real-time environmental data, with the help of interconnected devices, enhance the virtual experience such that it is in a physical location. Illustrating the use of the metaverse in diverse industries will help in understanding its impact on key factors, including transportation, healthcare, agriculture, and hospitality.

- **Healthcare:** In healthcare, IoT devices can be used to monitor patients' health and provide real-time feedback. For example, a smartwatch can track a patient's heart rate and alert a doctor if it falls outside of a healthy range. Organizations are increasingly encouraging the use of digital solutions such as virtual care, remote monitoring, digital diagnostics, decision support systems, at-home prescription delivery systems, and self-service applications for education and social support in the healthcare industry. This shift towards digital technology has greatly improved industry capabilities and service accessibility. Additionally, the implementation of technologies such as artificial intelligence, cloud computing, augmented reality (AR), and virtual reality (VR) has further enhanced the patient-clinician experience (S. M. Lee & Lee, 2021).
- **Transportation:** In the transportation field, IoT products can play an essential role in route optimization, and life will be much easier through the main road. Interconnected vehicles can talk to each other or traffic lights, allowing all the paths to run smoother. In the metaverse, such touch as a whole is beautifully plain to those who venture into driving simulations. This technology can be utilized to build a "wise traffic guard" for autonomous vehicles (AVs) via a smart windshield that shows real-time data. On the other hand, augmented reality can add virtual objects to real objects. (Njoku, Nwakanma, Amaizu, & Kim, 2023). Vehicle information on speed level, gasoline level, dangerous situations, or warnings may be displayed on the windshield. By combining GPS, GSM, and automobile authentication with Metaverse, an antitheft tool can be created. This device would possibly permit users to a designated place of their vehicle and restrict the vehicle movement of the car if it has been stolen(Njoku et al., 2023).
- **Manufacturing:** In manufacturing, IoT devices can be used to track inventory and optimize production processes. Sensors can be used to monitor the performance of machines and predict when maintenance is needed. Conversely, this technology can be used to create virtual factories that allow users to simulate manufacturing processes. BMW is not the only company that uses augmented reality (AR) to speed up the process of designing and creating new products. According to Luis Bollinger, one of the cofounders of Holo-Light, a company that specializes in extended reality (XR) streaming, many other companies are also finding AR to be a useful tool for reducing product development expenses and shortening the time it takes to bring products to market. Holo-Light is a company in which BMW is currently used to stream and work on 3D graphics("Six use cases for the metaverse in business | Nokia," n.d.).
- **Agriculture:** IoT devices can be applied in agriculture to gauge the moisture level of soil, suggest water flow on the basis of weather situations, and automated irrigation is based primarily on water requirements for plant life. This helps

with the efficient use of assets and could result in better crop yields and much less of an effect on the environment. The use of metaverses can help promote sustainable agriculture and efficient cultivation. The aggregate of the IoT and the metaverse era gives a variety of opportunities inside the agriculture industry, with the ability to brand spank new use instances and frameworks for Agritech. For example, IoT sensors can be utilized to display the increase in organic plants below unique weather situations. These records can then be shared with crop insurance corporations and banks to adjust charges and offer economic assistance in instances of drought. Furthermore, customers can place orders for agricultural products via cellular apps that make use of IoT facts to provide records on product excellence and availability (Bhat, AlQahtani, & Nekovee, 2023).

- **Energy:** IoT devices can be employed in energy industries to help monitor and analyse power consumption in homes and structures. More specifically, smart home automation can include controlling heating and cooling depending on people's presence by utilizing smart thermostats and monitoring energy consumption through the use of smart meters that provide feedback to the consumer. In the case of the metaverse, aspects of virtual energy systems that can provide users with information on how they use energy to promote sustainable practices can be developed.

- Metaverse and AR/VR are some of the key technologies widely integrated into Industry 4. 0, and they can be utilized in the energy sector to improve activities across four different subsystems: the smart grid, microgrid, electrical equipment, and energy trading. AR/VR generation can establish a technological simulation of the physical surroundings by using factors that include the stimulation of the senses and virtual imagery. The purpose of AR is to draw attention to certain features of the physical environment, to increase the know-how and focus of these functions, and to provide information that is beneficial and relevant to normal lifestyles. In contrast, VR technology provides the user with a computer-generated reality via eye-appealing visuals and objects to provide the user with the feel of the environment around them (Singh et al., 2022). This is made possible by a VR headset helmet or other similar VR equipment worn by the trainees. AR/VR technology can also be applied to save energy, reduce costs, reinforce safety, and provide effective training per the energy sector's requirements.

- **Hospitality:** IoT devices can be used within the hospitality industry to create a personalized environment on the basis of customer preferences and historical activity logs. Activities such as adjustment of lights and temperature, favourite music, and customer-specific room service can be useful for better profiling preferences. In the metaverse, virtual hotel rooms can be created to provide guests with an immersive preview of their resorts before they arrive.

The utility of metaverse technology in the hospitality and tourism industry is in a primitive stage, but there have been several recent developments in its utilization. Virtual tours of rooms and facilities permit customers to feel for the hotel earlier than they stay in the room. Recently, a few travel agencies have utilized the metaverse to create virtual tours of famous destinations, enabling customers to discover a destination before deciding (Gursoy, Malodia, & Dhir, 2022).

- **Education:** IoT devices can be used in education to create more interactive and personalized learning experiences. For example, sensors can be used to track student progress and provide real-time feedback, whereas smartboards can be used to deliver dynamic and engaging lessons. Conversely, virtual classrooms can be created to provide students with immersive and interactive learning environments. Training is one of the most practical applications of metaverse technologies, and it emerged as the most compelling use case according to our survey. Specifically, virtual reality (VR) can facilitate collaboration without the need for costly and time-consuming travel to a central training site.

Gilberto Serra, who serves as the head of digitalization at Nokia People Services, is responsible for overseeing the creation of the Nokia Learning Space. At the Nokia learning centre, this VR training environment is constructed with a 3D gaming engine that is typically used for developing video games. However, the training offered within the learning space goes beyond simply replicating physical activities in a virtual setting. By incorporating VR and AR technologies, it is possible to reveal normally invisible aspects of training. For example, in the real world, radio waves emanating from a 5G base station are not visible to the naked eye. However, in VR and AR, these waves can be made visible, which helps trainees better comprehend the technicalities of antenna beam-forming and other similar capabilities("Six use cases for the metaverse in business | Nokia," n.d.).

3.2 Different Dimensions of User Experience

This paper aims to discuss several elements in the context of users interacting by means of virtual spaces: effectiveness, inclusiveness, attractiveness, ease of use, and pleasure. Furthermore, it presents a discussion of the IoT into the Metaverse and ways that would improve user engagement through data and interactivity. Specifically, each section specifies major concerns and difficulties when aiming to design the best user experiences in the Metaverse to offer.

- **Performance within Virtual Environments**

In virtual environments, performance is one of the most important keys that affects the overall user experience. According

to different studies, system performance plays a vital role in determining user satisfaction and engagement by considering responsiveness as well as reliability. Web performance refers to the speed at which an application can be observed by users, and runtime performance refers to the speed at which an application responds to user commands (H. Wang et al., 2023). High-performance systems are designed such that they minimize latency and provide smooth experiences for users in metaverse-like platforms.

- **Accessibility of Digital Interfaces**

Digital interfaces should be accessible so that people with various disabilities can use them. The Worldwide Web Consortium's (W3C) Web Content Accessibility Guidelines (WCAG) 2.0 provides a holistic approach toward making information on websites accessible, considering the principles of perceivability, operability, understandability and robustness ("Web Content Accessibility Guidelines (WCAG) 2.1," n.d.). Accessibility is not about following rules; it is about promoting an all-inclusive environment where every user, irrespective of his or her limitations, can participate fully. The development of accessible player experiences in digital games is a key area of focus for creating fair digital experiences (Power, 2020). Ultimately, the responsibility for ensuring digital accessibility lies with those who design and construct the digital environment (Horton, 2022).

- **User Experience Desirability**

Desirability is the aspect of a product that addresses its emotional and visual appeal, thereby trying to affect users' motivation and engagement. (Seo, Lee, Chung, & Park, 2015) further explored the relationships among perceived usability, aesthetics, and emotional responses and reported that both perceived usability and aesthetics positively correlate with emotional valence and negatively correlate with emotional engagement. (Spillers, 2004) and (Barnum & Palmer, 2010) both underscore the significance of emotion in product design, with the former suggesting that emotion is a critical component of artifact sensemaking and the latter discussing the use of product reaction cards to measure desirability. (Verhagen, Feldberg, Hooff, Meents, & Merikivi, 2012) extended this discussion to virtual worlds, identifying visual attractiveness as a key motivational driver for user engagement. In contrast, creating environments that are visually and emotionally appealing aids in keeping people engaged.

- **Digital System Usability**

Usability here refers to how easy it is for people using the system or product to navigate within it and interact with it. The concept of usability in digital systems, particularly in the context of academic digital libraries, is multifaceted. (Jeng, 2005) and ("CambridgeCore_Citation_29Jun2024," n.d.) both emphasize the importance of effectiveness, efficiency, satisfaction, and learnability in assessing usability. (Jeng, 2005) further identified "ease of use," "organization of information," "terminology and labelling," "visual attractiveness," and "mistake recovery" as key user criteria. However, (Hornbæk & Law, 2007) caution that these measures are not always correlated and that users' perceptions may not align with objective measures. Therefore, while these criteria are important, they may not always be reliable indicators of usability.

- **User Engagement in Virtual Environments**

User engagement is the extent of the attention, curiosity, interest and emotional investment exhibited by users as they interact with a product. Research on the usability of digital systems, particularly metaverse systems, emphasizes the importance of user engagement. (Lalmas, 2012) defines user engagement as the quality of the user experience, which is crucial for maintaining concentration and motivation, especially in immersive environments such as the metaverse. (H. J. Lee & Gu, 2022) and (Zuo & Shen, 2023) both highlight the significance of user control, content, and interface design in enhancing user engagement in the metaverse. (H. J. Lee & Gu, 2022) specifically focused on the usability of digital native participants, whereas (Zuo & Shen, 2023) explored the role of features and affordances in engaging users. These studies collectively underscore the need for high usability in digital systems, particularly in the metaverse, to prevent user frustration and enhance overall satisfaction.

- **Integration of the IoT in the Metaverse**

Integration of the IoT within the Metaverse enhances the level of engagement due to timely and responsive data as well as interactions. Similarly, edge cloud computing attempts to offer low latency for real-time activities through edge computing, which normally processes data near the source. The addition of IoT devices to Metaverse is helpful with respect to Metaverse development because it enhances users' engagement via real-time data sharing and communications (Asad, Otoum, & Fandi, 2023). This is further supported by the use of edge cloud computing, which aims at attaining low latency for real-time interaction (Liu, Wang, & Zhao, 2022). However, these advancements also raise significant security and privacy concerns, particularly in the 'Metaverse of Things' (Pal, Vangala, Jadidi, Hóu, & Das, 2023). To address these concerns, strong security measures must be taken to safeguard user information. The convergence of metaverse and mobile edge computing offers a potential solution, with a proposed Fog-Edge hybrid computing architecture that can reduce

latency by 50% (Dhelim et al., 2022).

3.3 Methodology

This research uses a cross-disciplinary methodology to analyse IoT device integration within the context of the Metaverse. Information was gathered from research involving literature, whereby articles and journals strictly from reliable online media in the form of journals, reports, and case studies were considered. Hence, from an exploratory perspective, the authors applied a qualitative analysis to quantify prominent themes and issues concerning the IoT. Furthermore, interviews with experts were carried out to further investigate functional implementation and possible remedies. This methodology affords an all-encompassing approach to the research topic; thus, it forms a firm approach to the examination performed in this paper.

3.4 Conclusion

Given the existing and prospective extensive use of Metaverse for creating various exciting and captivating inside digital spaces, it is indispensable to harmonize performance, accessibility, desirability, usability, and user participation. From the usages perspective, all these aspects are rated towards better user experience; hence, there is a need to incorporate all of them in the development of a successful Metaverse. Further research is necessary to learn how all these components can interact in other ways, such as with emerging technologies such as the IoT, to improve the user experience.

4. Theoretical Framework for Components of User Experience in the Metaverse

The main result of the IoT at the user level has been the enabling of user interaction with the surrounding environment through smart devices. Owing to the use of sensors, the users can acquire an update in real time and practical notices and alarms and open complex systems using just one centrally connected device. This has made it possible for designers to develop better experiences, thus enabling them to design engaging environments compared with the past, thus improving the user experience.

To design experiences that are centered around the user, designers must look into elements such as the physical and digital interfaces of Metaverse. This concern concerns not only the physical behaviors of users but also their emotions and cognition, which are not necessarily cohesive with attitudes. It is thus possible to obtain information concerning these elements and thus the overall picture of the users and their experience using IoT technologies. It can then be beneficial to designers in targeting and providing content or notifications on the basis of users' interests and activities. With new data collected by sensors of devices such as smartphones or smart wearable accessories, designers step by step improve the UX in the Metaverse.

4.1 Critical Components of User Experience

The critical components, such as performance, accessibility, desirability, usability, and user engagement, collectively enhance the overall user experience. As illustrated in the diagram, the synergy between critical components and immersive technologies aims to provide a highly accessible and engaging digital environment.

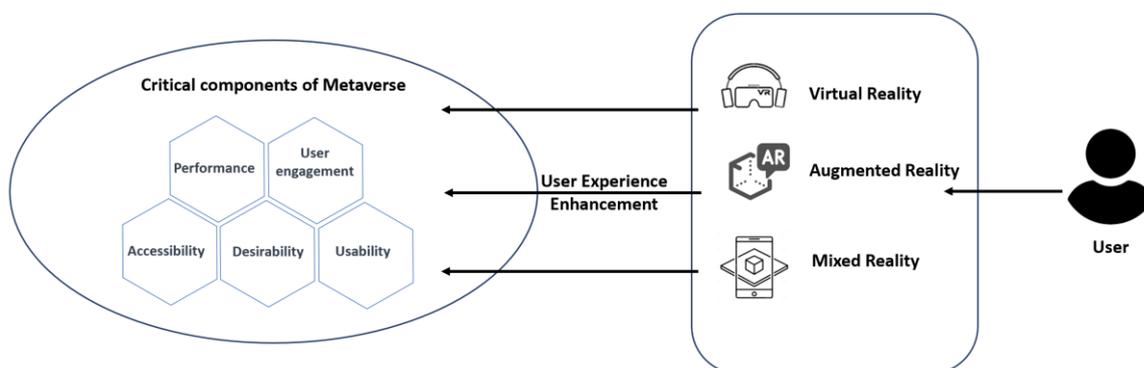


Fig 1. Critical Components of the Metaverse in the Context of User Experience

4.1.1 Usability

Usability refers to how easy it is for a user to navigate and interact with a product or service. Usability is an attribute that evaluates how a user interface can be easily used and refers to a method to improve the ease of use during the product or system design process (“USABILITY | English meaning - Cambridge Dictionary,” n.d.). Nielsen defines five initial usability criteria: learnability, efficiency, memorability, error, and satisfaction. Memorability refers to how easily the user can remember how to use a system even if it is not used frequently. The error should not be severe and should not occur in normal user scenarios. Satisfaction measures how easy and enjoyable the system is to use.

Table 1. Definition of Usability

| Component | Definition | Reference |
|-----------|--|--------------------------------|
| Usability | <ul style="list-style-type: none"> Usability is one of the key factors for the metaverse platform. The metaverse platform has complex characteristics of games, virtual reality, and social media, which can make it challenging for users to navigate and use effectively. Improving usability is important for enhancing the user experience in the metaverse. | (H. J.; Lee et al., 2022) |
| | <ul style="list-style-type: none"> Usability refers to the degree to which a particular product or system can be utilized by specific users to accomplish predetermined objectives in a given context, while also ensuring efficiency, effectiveness, and satisfaction. | (Zaharias & Poulymenakou, 1AD) |
| | <ul style="list-style-type: none"> Usability is all about how well a Metaverse platform works and how easy it is for people to use. When we talk about usability, we're talking about the relationship between users and the platform itself. This includes things like how the platform looks, how it works, and how reliable it is. It is important that users feel comfortable and safe when they're using the platform, and that they can trust it to meet their expectations. Interaction is a big part of usability too. That means everything from how the platform responds to user input to how it makes people feel when they're using it. All of these things work together to create a great user experience. | (Jeon, 2021) |

The usability of products and services is highly dependent on the design of their user interface. Learning duration, performance rate, errors, and end-user satisfaction make up success components that are impacted by the attribute. Thus, usability in the context of the metaverse points to how convenient it is to engage with the environment. Hence, usability is a crucial factor in increasing the possibility of a better user experience in the context of the metaverse (H. J.; Lee et al., 2022).

This includes the basic tenet of good usability, as this would enhance the interaction of this society within the metaverse, especially with respect to disabled persons. This means that everyone can produce a similar output, which is good, especially for limited outputs. For example, people with visual impairments obtain usability features that contain accessibility components such as color and typography.

The IoT's place in the metaverse directly relates to usability because it may further enhance the user's ability to interact with the environment because of its natural monitoring and recording of various processes within the virtual world. For example, placing environmental sensors on an actual real-world item could allow the item to be duplicated in the metaverse for use by various other people. This could make it possible for users to interact directly with physical objects in the real world with an embodiment of the characteristics in the metaverse, including switching on a light or setting the temperature in their homes. Moreover, IoT devices can report users' behavioral patterns and preferences in real time, which enables the metaverse to present itself as unique to the users. For example, the metaverse could change the lighting and temperature of a user's environment on the basis of wearable data used as part of the metaverse.

In general, the combination of the IoT with the metaverse could have a major impact on usability since users are offered more intuitive ways to engage with the environment and the products or services offered in it. more natural and intuitive

ways for users to interact with digital products and services.

4.1.2 Accessibility

Accessibility in the metaverse is crucial because virtual worlds have the potential to create new barriers for people with disabilities if they are not designed with accessibility in mind. The importance of considering accessibility from the beginning stages of metaverse development, including the use of assistive technologies and the inclusion of alternative ways to interact with digital environments, would be beneficial for everyone.

Table 2. Definition of Accessibility

| Component | Findings | Reference |
|----------------------|--|---|
| Accessibility | Web Content Accessibility Guidelines (WCAG) 2.0 defines accessibility as the degree to which a website, web content, or web application can be accessed and used by people with disabilities, such as visual, auditory, physical, speech, cognitive, and neurological disabilities. Accessibility is achieved when web content is designed and developed in a way that allows all users to perceive, operate, understand, and interact with the content, regardless of their abilities or disabilities. The WCAG 2.0 provides a set of guidelines and success criteria that web developers can follow to ensure that their content is accessible to a broad range of users, including those with disabilities. | ("Web Content Accessibility Guidelines (WCAG) 2.0," n.d.) |
| | Accessibility is the practice of making information, activities, and/or environments sensible, meaningful, and usable for as many people as possible. Accessibility is a practice of inequitable, responsible design. | ("What is Accessibility: An Introduction SeeWriteHear," n.d.) |
| | The design is of information systems such that they can be used by everyone, regardless of their ability or disability. | (Nganji, 1AD) |
| | Any product, service, technology, or environment is accessible and available to everyone, including individuals/learners with special needs | (Sani-Bozkurt, 1AD) |

Despite the emergence of new metaverse products, such as games and social applications, the issue of accessibility has been largely overlooked. In particular, many videos within the metaverse are not designed to be accessible to users with disabilities. This means that captions, audio descriptions, and language that describe what is happening onscreen are often missing. As a result, visually impaired or blind users may struggle to fully engage with metaverse content, creating a significant accessibility challenge (Mitchell Park, 2021). Accessibility should be considered from the beginning stages of metaverse development. This includes the use of assistive technologies, such as screen readers and alternative input devices, as well as the inclusion of alternative ways to interact with digital environments.

4.1.3 Desirability

The desirability component in the metaverse requires a deep understanding of the emotions and motivations of users, as well as the ability to design experiences that elicit positive feelings and engagement. The importance of considering factors such as cultural context and personal identity when designing virtual environments is necessary to satisfy the persona of the user.

Table 3. Definition of Desirability

| Component | Findings | Reference |
|---------------------|--|---------------------------------|
| Desirability | The capacity of a product or system to encourage a user to engage with it, obtain it, or interact with it. | (Silva & Simoes, 2011) |
| | Desirability refers to the subjective factors associated with taste and aesthetics, which make a product or brand appealing to users. The importance of desirability lies in its ability to attract and engage users, thereby encouraging them to explore the product's features | ("What is desirability?," 2023) |

and functionality. This initial engagement can lead to a deeper understanding of the product's usefulness and usability.

The intangible aspect of a good user experience is its desirability, which encompasses factors such as perceived enjoyment, aesthetic appeal, and the satisfaction derived from using the product in its intended context. The look and feel of the product play a crucial role in its desirability, contributing to the overall pleasure of the user experience. (Goodman, Kuniavsky, & Moed, 2013)

Therefore, the desirability of the metaverse implies the extent to which the environment facilitates and fosters social interactions among users. This can also include, for example, the option of chat, group tasks, exercises, or other experiences. Desirability might be an occurrence of quality in the virtual space. This can range from the appearance of the façade, music and sounds, to the overall environment of the place. The IoT may also finally unlock the desirability factor in the metaverse by providing new ways to interact as well as improve users' experience in the context of the metaverse. IoT devices can also detect user preferences as well as their behavior and hence can be used to improve the user experience in the metaverse.

4.1.4 Performance

Performance in the context of a metaverse user experience generally refers to the speed and responsiveness of an application. It can be defined as the time it takes for a user to complete a task or achieve their goal within the system. In addition to speed, performance can also include factors such as reliability, stability, and scalability.

Table 4. Definition of Performance

| Component | Findings | Reference |
|-------------|---|-------------------------------|
| Performance | Performance is a critical aspect of quality that relates to the speed at which an application operates. In the context of web applications, performance can be broken down into two distinct components. The first is web performance, which refers to the time it takes for the application to be presented to users. The second is runtime performance, which refers to the speed at which the application responds to user interactions. Both of these facets of performance are essential to the overall user experience and warrant careful consideration. | (Barker, 2012) |
| | The effectiveness of service-oriented systems in carrying out their intended functions can be assessed through the measurement of their throughput and response time. | (Y. Wang, Jiang, & Pan, 2018) |
| | This concept refers to the degree to which predetermined goals for a specific purpose have been attained, encompassing both the quality and quantity of the outcomes achieved. | (Tamer, 2022) |
| | The execution of action, behavior, or accomplishment of a task is measured against self-set or external standards of accuracy, completeness, cost, and speed. | (Govender, 2020) |
| | Need to be measured for both the aspects quantitative (delivery lead time, flexibility, and resource utilization), and qualitative (service/product quality and customer satisfaction). | (Gupta, 2022) |

The Internet of Things (IoT) can play a key role in increasing the performance of the Metaverse. IoT devices can collect real-time data about user behavior and preferences within the Metaverse. These data can be used to improve the performance of the Metaverse by optimizing content delivery, improving user engagement, and providing personalized experiences. IoT devices can be used to monitor the performance of the infrastructure that supports the Metaverse, such as servers and networking equipment. This can help identify potential issues before they become major problems and ensure that the Metaverse remains highly available and responsive.

4.1.5 User Engagement

User engagement refers to the quality of the user's experience while interacting with the virtual environment, emphasizing

the positive aspects that encourage users to spend more time and engage repeatedly. This is a crucial aspect of metaverse design, as successful virtual worlds are not only used but also actively engaged with by their users. Users invest their time, attention, and emotions in exploring the metaverse and seek to satisfy both practical and pleasurable needs while doing so.

Table 5. Definition of User Engagement

| Component | Findings | Reference |
|------------------------|--|------------------------------------|
| User Engagement | User engagement is the emotional, cognitive, and behavioral experience of a user with a technological resource that exists, at any point in time and over time. | (Lalmas, O'Brien, & Yom-Tov, 2014) |
| | User engagement is a user's response to an interaction that gains, maintains, and encourages their attention, particularly when they are intrinsically motivated | (Holdener, Gut, & Angerer, 2020) |

Conversely, users will have a plethora of options to engage with brands and products. They can browse through virtual storefronts, shop in a virtual store, select products from shelves or racks, and even seek advice from virtual store employees. They can try on clothes in virtual dressing rooms and add products to their virtual carts(Geert Leeman, n.d.).

These are just a few examples of the endless possibilities in the metaverse. While some brands may choose to recreate their physical stores in the virtual world, others may opt for entirely new and unique experiences. For example, Nike recently introduced Nikeland, a virtual environment in which the customer interacts with a brand that is entertaining and interesting. Another is Hyundai Motor Company's Mobility Adventure, which is a communal virtual platform that allows users to engage with Hyundai's vehicles and products and partake in different theme parks(Geert Leeman, n.d.). The metaverse opens many possibilities for brands to be as close and relevant to their audience as possible and offer them unique and engaging experiences that are not conceivable in real life.

As a result of IoT technology, virtual environments can be enhanced in terms of the interactivity that is accompanied by such devices. For example, a smart home system can be integrated into a user's metaverse to enable the user to interact with his/her metaverse environment physically in addition to voice control. Such a level of interactivity can increase the user's level of presence and invested involvement in the metaverse. Furthermore, IoT devices can provide information about users' activities and preferences in the metaverse and adjust the metaverse depending on the user. It is a way of engaging users in new things, and this can help since users can be provided with content that is interesting to them. For example, the fitness tracker of a user could be linked to his/her metaverse character; the character can receive a customized workout regimen and missions. It can be argued that the IoT can improve the user experience in the metaverse through increased engagement. This means that users take more time in the metaverse, thus increasing their interest in their avatars and, in turn, leading to a healthier metaverse ecosystem.

4.2 Design considerations

4.2.1 Metaverse Architecture

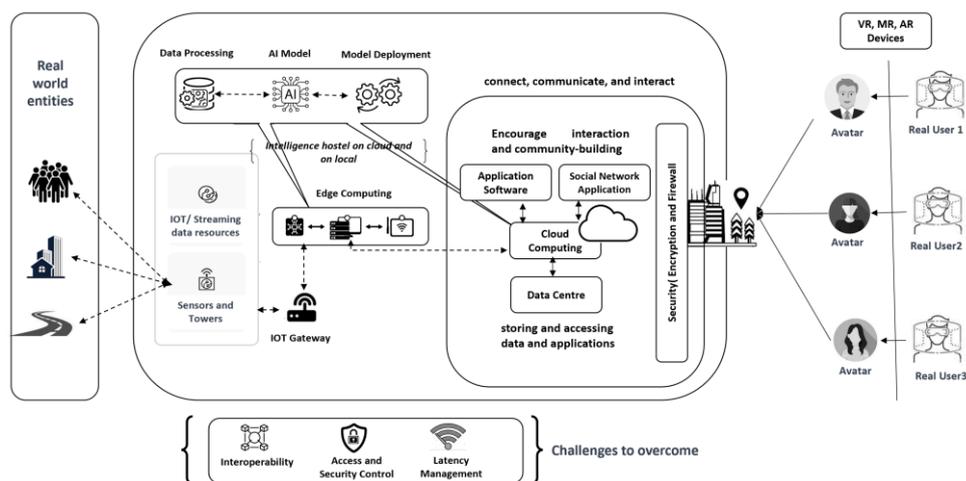


Figure 2. Metaverse Architecture

This diagram illustrates the comprehensive framework of integrating real-world entities with IoT infrastructure, data processing, and AI models to enhance user interaction and community building in a secure and efficient manner via VR, MR, and AR technologies.

- **Real World Entities:**
 - People, buildings, and infrastructure are represented as real-world entities that interact with IoT devices.
- **IoT Infrastructure:**
 - **Sensors and Towers:** Collect data from the real world.
 - **IoT/Streaming Data Resources:** Process and stream real-time data to the IoT gateway.
 - **IoT gateway:** This gateway serves as a bridge between IoT devices and the data processing system.
- **Data Processing:**
 - **Edge Computing:** Processes data locally to reduce latency and bandwidth usage.
 - **AI Model:** AI can be used to analyse and interpret data.
 - **Model Deployment:** AI models are distributed to various applications for further use.
- **Connectivity and Interaction:**
 - **Application Software:** Facilitates user interaction with data and applications.
 - **Social Network Application:** Enables community-building and user engagement.
 - **Cloud Computing:** This provides storage and computing power for data and applications.
 - **Data Centre:** Centralized storage and management of data.
- **Security:**
 - **Security, Encryption, and Firewall:** Ensuring data privacy and protection.
- **VR, MR, AR Devices:**
 - **Avatars:** Represents real users in virtual environments.
 - ****Real User 1, Real User 2, Real User 3**:** Individuals interacting with the system through avatars using VR (virtual reality), MR (mixed reality), and AR (augmented reality) devices.
- **Challenges to Overcome:**
 - **Interoperability:** Ensuring that different systems and devices work together seamlessly.
 - **Access and Security Control:** Managing who can access the system and maintain security.
 - **Latency Management:** Reducing delays in data processing and transmission to improve real-time interaction.

4.2.2 User Interface of the Metaverse

The interaction that occurs between the user and the virtual environment must be designed such that the IoT devices are incorporated and used easily by the users. However, the interface should be good, simple to use, and should not overload the user with too much information. The user interface can be described as how a person communicates with a machine or a gadget. The GUI is a relative superstrate that enables the user to input information by touching the screen, by the voice that is speaking to it or by moving hands in various ways relative to the machine; the superstrate also provides multiple ways of giving output information to the user through vision, sound, and feelings (Thomas Barton Schalk Paola Faoro, n.d.). The interface must be developed in such a way that it will incorporate all the IoT devices in the best way possible. This implies that designers need to make the interface of IoT devices friendly enough for users to enable them to control and manipulate them. This paper emphasizes that designers can create a user interface in such a way that it naturally includes IoT devices, thereby entertaining the user.

4.2.3 Sensors and Towers

WSNs (wireless sensor networks), which are categorized as IoT (Internet of Things) devices, collect and condense data related to space, the environment, or physiology. This ambient information can enrich the exogenous information and

provide useful information and data to the end-users (Saba, 2011). The sensor is an element that is employed when gathering information concerning the current state of the environment under scrutiny. These are IoT devices that are required to interface with low-cost devices that collect the data and forward it to the central data processing engine. This information from the sensors is employed to build a machine-learning model to produce an ongoing picture of the target setting.

This means that there is a need to acquire data on the physical characteristics of the world and encode it into a format understood by a computer. For example, a camera sensor can gain light reflected from real-world objects and convert that light into data that can be rendered on a screen. Likewise, temperature can be measured to check its variations and passed into a form that can be understood digitally and displayed on a computer.

Other sensors, such as accelerometers, gyroscopes, and magnetometers, may also offer data concerning the motion and position of a tangible object in a real-world environment. In our case, the information received from several sensors helps to build an accurate depiction of the real world. The other sensors incorporated in IMUs include accelerometers for calculating acceleration by measuring the change in position over a certain period, gyroscopes used to determine the rotational rate of an object and magnetometers that determine the magnetic field around an object. Acceleration is the rate of change in velocity, and accelerometers measure linear acceleration. Gyros have an input of angular velocity, which is the rate of change in orientation. Magnetometers are instruments that are used to determine the intensity and orientation of a magnetic field. These sensors are crucial for the attitude control of drones and other uses where one needs to know the orientation and movement of their equipment. However, they are strongly affected by systematic errors, and their calibration often needs to be performed quite often (Jacky C. K. Chow Jeroen D. Hol, n.d.).

It can be utilized in virtual reality, augmented reality, and simulation, among other applications. For example, virtual reality headsets have sensors that follow the direction in which the wearer is facing and develop a picture that is similar to what is being seen. This has wide implications in different disciplines of learning, training, education, and, most likely, entertainment. Sensors are also found in virtual reality headsets to capture and establish the motion and direction of the head of the user. These are usually accelerometers, gyroscopes, and magnetometers that help in the determination of the motion of the user's head in three planes. This information is used to update the user's view of the virtual environment in real time, thus giving the user the impression of being present there. (Fuchs, n.d.).

4.2.4 Personalization of the virtual environment with the use of AI and ML

It is also possible to leverage the IoT devices in the Metaverse to gather user behaviour and preference data for its use in personalizing the Metaverse. The IOT sensors can collect data and forward them to the processing sections. The resulting information can be utilized in modelling and testing machine learning models. The kind of information that these sensors collect 'may change with the type of application' but may encompass the 'temperature 'humidity levels' pressure 'light intensity' sound' and even motion. With the help of machine learning methods, these data can be analysed to gain much insight. To explain the potential of machine learning in the IoT, one can identify the main areas where machine learning techniques can be applied in the context of the IoT, namely, data analysis of enormous amounts of data produced by various IoT devices and device control to enhance the decision-making process. IoT data can be analysed with the help of machine learning patterns for detecting patterns, anomalies, and trends; predictions based on historical data are also possible. All of these factors can help organizations become more efficient, provide value for their money, and effectively improve the quality of the services they offer to customers (Sachs, Petrov, & Guerrero, 2010).

Designers must consider how such data can be utilized to make the user experience more orienting and engaging. Understanding is achieved depending on the goal and may include the customization of the avatars and the objects within the environment according to the user's context, preferences, or mood or the use of personalized suggestions concerning the activities or other usable interfaces. Using data gained from IoT devices will eventually help designers develop a more entertaining and satisfying experience for users at the virtual level. Big data is going to be a trend because of the sheer number of connected devices there and machine learning (ML) is going to help in processing all these data. This will make IoT devices even more valuable, and the IoT itself, in turn, will be utilized even more profusely. Running down the middle of all this will be embedded intelligence (EI), a process by which a product is infused with intelligence to acquire higher levels of automation, efficiency, productivity, and connectivity. Regardless of offline or online intelligence, it is a process that is derived from learning (Guo, Zhang, & Wang, 2011).

5. Utilization of IOTs in metaverse architecture and its challenges

As the Internet of Things (IoT) becomes more integrated into the metaverse, there are both benefits and challenges to consider when designing this new platform. Latency can be a significant issue that must be addressed to ensure that information transfer between real and virtual spaces is accurate. Additionally, device compatibility is important, as

developers need to ensure that their applications or games work properly with popular devices found in homes or offices. By addressing these issues, designers can create optimal performance and user experiences when building metaverse devices with IoT-connected devices.

5.1 latency

One major issue with using the metaverse is latency, which is the delay between actions initiated by users and when their avatars reflect those actions. This loss of synchronization with the real world can negatively impact the metaverse experience, and the solution requires controlling latency and improving the experience for users. This involves not only edge computing but also edge connectivity, such as faster broadband and minimizing the number of devices and hops between the user and the software that interprets their actions. It is important to have fast and direct paths between the user and the nearest edge. Since the metaverse is accessible from anywhere where social media users are located, it is important to consider connectivity everywhere (“Surprise! The metaverse could be great news for the enterprise edge,” n.d.).

To ensure a smooth transition between real-world and digital environments, developers must also pay attention to matters such as device compatibility, the appropriateness of user input, connectivity or latency issues, security protocols, and the implementation of augmented reality capabilities. Designers need to consider how their innovations can complement existing practices within the metaverse, creating a more cohesive user experience for all participants. Addressing these points before launching an application will ensure optimal results when navigating and enjoying content in the increasingly crowded metaverse.

The solutions cannot incorporate such elements as artificial definitions or depend on the central data. This is why distributed architectures must be used for devices so that they can freely communicate and exchange information with no need for access, control, or trust. Designers must also consider the interface and usability; users may not be familiar with physical and digital IoT devices. Additionally, the security of the systems must be analysed in detail to ensure that having interconnected systems does not leave them vulnerable to cyber criminals. As a result, with proper strategizing of development and application design, developers can make outstanding applications that further embrace the new age of the online world, which is linked with the help of virtual as well as augmented reality and with the help of IoT-integrated systems.

This view suggests that to avoid latency, designers must address certain issues, such as connectivity, data processing, and device compatibility. I observed that it is possible to reduce these and other latencies by optimizing these factors so that the virtual environment would become more responsive for the users. In summary, the management of latency is an instrumental factor in improving the quality of the users' experience in the Metaverse.

5.2 Privacy and access control

The IoT environment involves the collection and transfer of sensitive data to applications with little or no human involvement. This creates the challenge of safeguarding the security and privacy of millions, if not billions, of users. To address this issue, access control techniques should be implemented to restrict access to these data and information (Andaloussi et al., 2018).

However, designers must also consider user privacy concerns and ensure that data are collected and used ethically and transparently. In the IoT environment, several different attacks pose a real threat to the security and privacy of user data and applications. These include denial of service (DoS) attacks, distributed DoS attacks, spoofing attacks, jamming, and eavesdropping. To counter these threats, Xiao and colleagues proposed several access control methods that use classification, clustering, and reinforcement learning techniques. The overall goal of these methods is to protect user privacy in the IoT environment (Liang Xiao Xiaoyue Wan, n.d.).

In a recent study (Hussain, Hussain, Hassan, & Hossain, 2020), Hussain and colleagues conducted a thorough examination of various attacks, current state-of-the-art solutions, and challenges related to security in the Internet of Things (IoT) paradigm. The authors identified several critical security gaps and proposed the use of machine learning and deep learning techniques as potential security solutions in the IoT context. The study also outlined future directions for developing ML- and DL-based access-control solutions.

In another study (Hasan, Milon Islam, Ishrak Islam Zarif, & Hashem, 2019), several ML algorithms, including support vector machine (SVM), logistic regression (LR), random forest (RF), decision tree (DT), and artificial neural network (ANN), were used to predict various types of attacks and anomalies in the IoT environment. The decision trees and ANN performed better than the other methods did.

The Metaverse system enhances the real-world building environment by adding various features, such as virtual meetings, shopping in a virtual mall, and remote surgery. These functionalities are integrated into the system through different applications. However, the communication channels between these apps can create a backdoor for third-party tracking and

cross-app tracking, which can compromise users' privacy (Qi et al., 2015).

One solution to prevent this type of tracking is to block unnecessary tracking channels in the system. Apple and Google have already implemented strict cross-app tracking authentication in their mobile systems, which allows users to decide which app can track other apps. However, users may make mistakes or accidentally give away control (Kollnig, Shuba, Van Kleek, Binns, & Shadbolt, 2022).

Furthermore, the seamless interconnectivity of devices in Metaverse via Bluetooth and other communication protocols increases the potential for third-party tracking and cross-app tracking (Korolova & Sharma, 2018). To improve the solution, third-party tracking and cross-app tracking analysis tools and detection algorithms should be applied.

Considering the limited computational power of devices in the early metaverse era, a lightweight detection mechanism can be utilized to detect and block third-party tracking and cross-app tracking. This mechanism can include using a blocklist to block known threat requests and machine learning models to detect and block malicious activities from third parties (Cozza et al., 2020).

5.3 Interoperability

To provide a seamless and immersive experience in the metaverse, establishing strong technical interoperability between different hardware and software through a well-established network infrastructure is essential. This is similar to how webpages use TCP/IP for data exchange and HTML for presenting 2D information, where standardization is necessary to enable communication and interoperability in the metaverse ("Leading Standards Organizations and Companies Unite to Drive Open Metaverse Interoperability," n.d.).

To achieve technical interoperability, several aspects need to be reviewed, such as the data that must be exchanged across devices and networks, the timeliness of data exchange, file formats and data schemas, the artistic and stylistic interpretation of assets, and the computing power required for transmitted data processing. Several standard groups, including the Metaverse Standards Forum, the Open Metaverse Alliance for Web3 (OMA3) ("OMA3," n.d.), the Institute of Electrical and Electronics Engineers (IEEE) ("Why Are Standards Important for the Metaverse?," n.d.), and the Worldwide Web Consortium (W3C), are working towards addressing these technical interchange needs.

In addition to technical considerations, addressing network constraints, asset ownership, IP protections, payments, identities, data privacy, and security concerns at both the hardware and software levels is vital to creating a human-first metaverse. To achieve accessibility and inclusivity, designers must address localizing, reducing latency, and optimizing bandwidth to provide a similar sense of persistence and presence across metaverse experiences. Technical standards such as glTF ("Index of glTF/specs/2.0," n.d.) and universal scene description (USD) support data interchange interoperability across the infrastructure. Future best practices should cover functional usage and technical data interchange to enhance the overall experience of the metaverse.

6. Solution Approach

Edge Computing: Edge computing can help reduce latency by processing IoT data locally rather than sending it to a central server. This can help ensure real-time interactions in the virtual environment. Edge cloud computing is a distributed technological development architecture in which client data are handled at the network's edge, as near the actual source as permitted ("What is Edge Computing? Definition, Technology, Examples," n.d.).

In connection with the Metaverse, the utilization of edge computing is beneficial since it enables IoT data to be processed locally to the user instead of through the primary server. This can lead to quicker and less interrupted interactions for individuals in the virtual environment. This is because edge computing also assists in minimizing the amount of information to be transferred across the network, which also assists in decongesting the network and its optimization. Additionally, edge computing can enhance security since the users' data are processed directly on the end device and not routed through an insecure network. Thus, designers must consider how edge computing can be integrated into the Metaverse design, as well as how to determine if all the needed infrastructure is ready for such integration.

Analytics: Designers can gain insights into how people use their products and what their preferences are by using analytical tools. In this way, designers will be able to optimize the virtual environment for a more personalized and engaging experience. These analytic tools are thus important in shaping the design of the Metaverse. Designers can gain a better understanding of how users interact with the virtual world by analysing data from IoT devices, such as users' interactions with objects and devices. This enables optimization of the design of Metaverse to make it personally engaging with users. For example, designers may employ analytics to determine which parts of the virtual space are underused or causing frustration among users and proceed to rectify them to enhance the user experience generally. Moreover, analytics can also help monitor changes in user engagement over time so that designers can assess whether they have made progress or need to update their work accordingly. To ensure that they create a more captivating and personalized client experience,

designers must determine ways through which analytics can be integrated into designs for the metaverse.

Strong security protocols must be adopted to ensure that any IoT device is secure and that data about the user are protected. To make such a metaverse possible, stringent measures for security are needed to stop the unlawful abuse of information of the users being private. "Privacy" can be endangered by security holes, says Pauly in an email. These can possibly open devices for hacking or data breaching, which means that developers will have to implement the necessary security measures from an early stage. For this purpose, data can be secured in transit and at rest via encryption protocols and access control mechanisms, and authentication techniques ensure that only authorized personnel are granted access to sensitive files. However, any measures taken to mitigate the risks posed by the devices themselves also need to be considered before addressing the IoT security landscape. In this way, trust between the users and the developers within the Metaverse is built by placing stronger protective measures, ensuring that it becomes a haven for all. In conclusion, the impact of the IoT on the user experience in the Metaverse can be significant. Designers must carefully consider design considerations, challenges, and solutions when incorporating IoT devices into the virtual environment. By doing so, they can create a more immersive, engaging, and secure experience for users.

7. Limitations and Future Research

7.1 Limitations

While this article provides a comprehensive exploration of the integration of IoT devices into the Metaverse and their impact on the user experience, there are several limitations to consider. While this article provides a comprehensive exploration of the integration of IoT devices into the Metaverse and their impact on the user experience, there are several limitations to consider:

- **Lack of Empirical Data:** All the solutions suggested as well as possible designs are derived theoretically and not observed in practice from the reviewed articles. However, few scientific works support these concepts, and their effectiveness has not been demonstrated under real-life conditions.
- **Evolving Technology:** The two are relatively new and promising technologies, as they still exhibit growth in the market. It should, however, be noted that the constant evolution of technology means that while some of the solutions discussed here may be good at present, the situation may change in the future, making the solutions less effective.
- **Security Concerns:** Nevertheless, flexible security measures are proposed for strong security protocols; however, they do not discuss various types of security or their applications in detail. Importantly, as technologies such as IoT devices and metaverse platforms advance in the future, new security threats may always need to be addressed.
- **Interoperability Issues:** With respect to the concept of other articles, this article raises the question of interoperability quite often but does not describe how existing IoT devices can be seamlessly integrated into metaverse platforms.
- **User Diversity:** The exacerbation of IoT integration on different classes of consumers with an emphasis on the disabled is recognized but more cannot be fully investigated. Further research is required to acknowledge the expanded heterogeneity in people's usage of the IoT.

7.2 Future Research

To address these limitations and build on the findings of this article, future research should focus on the following areas. Therefore, on the basis of the limitations of this article and to advance this line of research in the future, the following areas are recommended:

- **Empirical Validation:** Conduct research to validate the identified design considerations and solutions in real-world settings. This can be performed with real users, with the help of performance measurements, and with the purpose of collecting feedback for verification and development of the mentioned approaches.
- **Longitudinal studies:** Thus, the use of IoT devices in homes and offices needs to be tested for a long period to deduce their impact in homes and offices. This will help in identifying trends of advantages that cannot be easily observed as well as drawbacks of the recommendations.
- **Advanced Security Measures:** Future studies should involve more emphasis and research pertaining to improving security for the Metaverse and, more specifically, for interfacing with the IoT. Therefore, much focus has been placed on the efficiency of building layers of security, and research has revealed more robust and practically applicable methodologies, as they may be extended with the emerging risks and challenges.
- **Interoperability Frameworks:** Additionally, there is a need to develop specific strategies that will refer to the integration of IoT devices with metaverse platforms, allowing for concrete guidelines concerning the compatibility of such devices with various metaverse environments. There will be many interactions with other players within the industry and standards bureaus.
- **Inclusive Design Research:** However, having analysed all the features and capabilities of integrating the IoT in Metaverse, it is necessary to determine the work of such a system for different categories of users, including persons with

disabilities. There should be studies concerning end-users: their desires, needs and/or issues that need to be considered to improve the accessibility of virtual environments.

- Technological advancements: The literature reviewed for the IoT and the Metaverse are the latest technologies available, and such technologies/trends are incorporated in the research findings/design solutions proposed within this context.
- These directions can aid in expanding the knowledge of the impact of the IoT on the user experience of the Metaverse in subsequent studies and enhance virtual environments' functioning, safety, and access. Prove the design, protection, and accessibility of virtual environments.

8. Conclusion

The Metaverse offers numerous exciting opportunities for many industries, and indeed, the involvement of IoT devices could improve users' experience in the Metaverse. Nevertheless, few problems have yet to be solved, including ethical and privacy questions, technical issues, and the demand for proper IoT devices and networks. These challenges will have to be met head-on as technology progresses into the future to guarantee that the Metaverse and IoT will complement each other and that the users of the said technologies will be given the best performance accompanying the experience. However, the opportunities of this technology are enormous, and we can expect that the future will only bring positive changes in the Metaverse and IoT, which will improve and develop our digital world. Thus, as shown in this article, several design considerations and solutions determine the integration of IOTs into the Metaverse. These are latency, security, and compatibility; these are significant hurdles, and overcoming edge computing could be one such solution by eliminating latency since data processing can be performed locally. Extremely relevant tools of data analysis allow us to gather profound information about users' behaviour to facilitate the individualized environment.

Again, the various possibilities of IoT integration in Metaverse are spectacular and can revolutionize virtually every economy, ranging from healthcare, transport, industry, farming, energy, tourism, and education. In this context, industries can incorporate today's trends such as AI and machine learning while using real-time information to capture the desired outcome of improved experiences that are rich in interactivity and highly productive.

However, if IoT devices have been incorporated into Metaverse in the right manner, then interaction and presence in the virtual world will be deeper while at the same time being safe. On this basis, by mitigating all these highlighted issues through coherent approaches to counter them, all designers can harness the potentiality residing in the IoT to introduce a new age of 'user revolution' in the metaverse and, in turn, establish oneness and innovation in the subsequent phase.

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