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Metaverse: Industrial Applications – challenges and opportunities

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Abstract

Metaverse is a concept that refers to a space where the physical and virtual worlds coexist in harmony through technology. Technologies such as virtual, augmented, and extended reality have introduced the necessary tools to overcome the challenges that arise in the Industrial Metaverse revolution. Thus, it is now more than ever essential and imperative to analyze, design, and develop applications, as well as the underlying infrastructure, and adapt the key enabling technologies that will facilitate the transition from Industry 5.0 to Metaverse. In this work, we aim to recognize the challenges, explore the technical advances, and present the solutions and applications that emerge towards a human centric, resilient and sustainable society.

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Keywords: Metaverse; Industry 5.0; Society 5.0; human-centricity; resilience; sustainability

1. Introduction

Metaverse does not yet have a typical definition although the idea has been around for years. It wasn't until the year 1992 that the author Neal Stephenson mentioned Metaverse in his novel "Snow Crash" [8] for the first time, where he described a virtual world where people can interact with each other. Years later Matthew Ball gives a first definition of Metaverse "A massively scaled and interoperable network of real-time rendered 3D virtual worlds that can be experienced synchronously and persistently by an effectively unlimited number of users with an individual sense of presence, and with continuity of data, such as identity, history, entitlements, objects, communications, and payments." [21]

It is now more critical than ever to analyze the challenges and seek opportunities that arise from the evolution of Metaverse utilizing the technologies associated with it and beyond. The revolutionization of Web 3.0 can foster productivity and enhance the industrial process to shift from Industry 4.0 to 5.0. Technologies such as extended reality (XR), robotics, sensors and actuators as part of the internet of things (IoT), artificial intelligence (AI), digital twins, development tools, blockchain, computing and connectivity. Industry 5.0 is a new concept that emphasizes the interaction between humans and machines. [22]

In this paper we analyze the applications and the technical parts being used in the industrial metaverse and how these affect the Industry 5.0. In the subsequent sections we give a generalized framework that embodies the Digital Twins with the blockchain technology and explain the structure and functionality. We also trace the evolution of World Wide Web to Web 4.0 and how this helps the interaction between humans and machines. Additionally, we provide insights into industrial applications and how Metaverse can be used as a tool for interaction and the challenges that occur from it.

2. Research Methodology

This section demonstrates how the review methodology was carried out in Scopus database. A Visualization of Similarities (VOS) chart, created using VOS viewer software, is presented in Figure 1 to illustrate the relationships and similarities

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between various entities, such as research papers, authors, and keywords within the datasets. The VOS diagram provides a useful tool to visualize the similarities among the retrieved scientific documents. The diagram uses nodes to represent individual entities and lines or edges to connect nodes that share common characteristics or co-occurrences.

Node size & color: The significance or relevance of each node in the illustration can be represented by its size in relation to the dataset. Nodes that are larger may signify papers that have been cited frequently, authors who are well-known, or keywords that are frequently used. The color of the nodes might convey additional information, such as differentiating clusters or categories of entities. Nodes of the same color often belong to the same group based on their similarities.

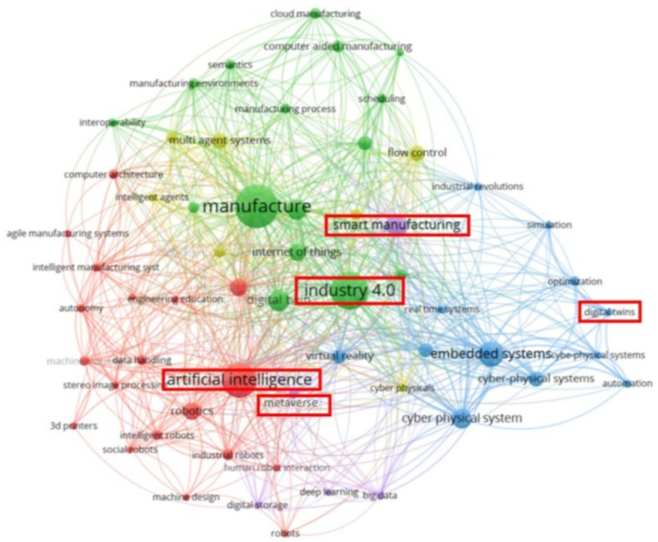

Figure 1: Visualization of Similarities (VoS) Scopus

Cluster Formation: Nodes that are situated near each other tend to have more similarities or occur together more often. This grouping process assists in detecting distinctive categories or themes within the dataset. Legend and Labels: Having a clear explanation and labels on the diagram can provide crucial details about what each node and edge signify. This helps the audience comprehend the context and significance of the visual elements. The total documents in Scopus database derived from the following search query were as follows: 159 (72 Conference papers, 66 articles, 9 book chapters, 7 reviews and 5 conference reviews).

3. Industrial Applications

3.1. Generalized framework for Metaverse ecosystem based on the integration of Digital Twins and Blockchain

In Figure 2, a generalized system architecture, which enables the expansion and interconnection of several industries beyond manufacturing based on the integration of key Industry 4.0 technologies. Among the most influential technologies are Digital Twins and blockchain. The designed platform for this intricate ecosystem faces numerous challenges to fulfil the specified requirements and ensure swift and secure interoperability among its diverse components. The proposed DT-enabled platform integrates multiple modules into a distributed architecture where various edge nodes collaborate to deliver optimal Quality of Experience (QoE) and Quality of Service (QoS). It is worth noting, that due to increasing computational power and the minimization of micro-processors and complete circuits, such smart and intelligent devices can be employed to the edge layer. By doing so, the computational burden of imposed in centralized systems can be avoided, along with the minimization of network traffic, since the amount of data on a theoretical level can be reduced. Further to that, with the integration of 5G and 6G wireless communications, data transmission and network reliability are two almost non-existent challenges. Both DT (Digital Twin) and XR (eXtended Reality) modules will work together on

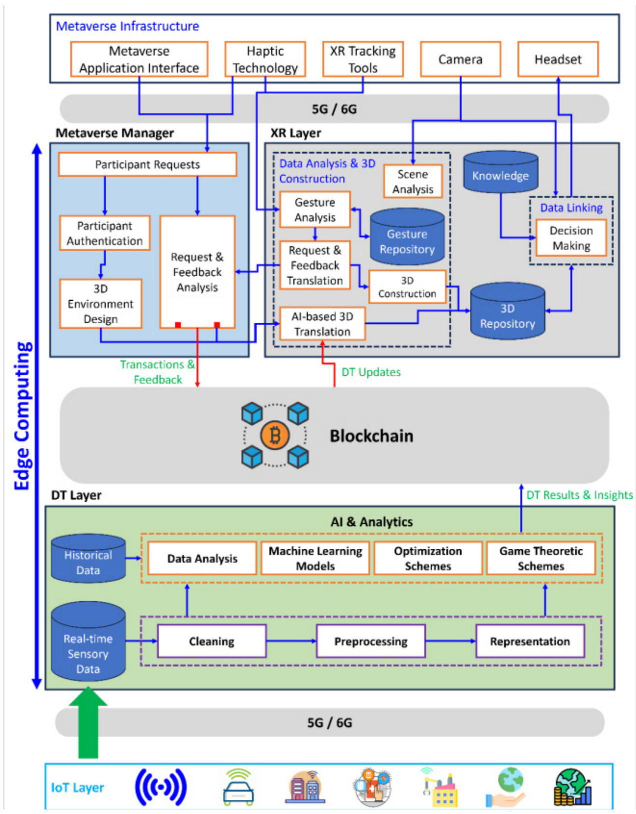

Figure 2: Generalized metaverse framework based on Digital Twin, eXtended Reality, Blockchain, and 5G/6G networks

these edge nodes, and their management must also be conducted at the edge. The provisioning and collection of real-world data should take advantage of 5G/6G communication to achieve exceptional service and user experiences in metaverse applications.

4. From Web 1.0 to Web 4.0

The creation and evolution of the World Wide Web (WWW) stands out as one of the most significant technological advancements. What began as a basic communication tool in the 1990s has transformed into a driving force for global communication, information and asset exchange, remote task execution, and collaborative group efforts [1]. Tim Berners-

Lee et al. introduced Web 3.0, also known as the Semantic Web, in their research [2]. The authors' vision for the structure of the Internet (as shown in Figure 3) emphasizes the integration of ontology-based frameworks to enhance machine comprehension. This development enhances the efficiency and accuracy of web-based processes. Web 4.0, or the symbiotic web, is the fourth generation of the World Wide Web, integrating artificial and ambient intelligence, Internet of Things devices, trusted blockchain transactions, virtual worlds, and extended reality. It envisions harmonious interaction between humans and machines, with a critical mass of network participation for global transparency and collaboration [3]. The goal is to enhance internet inclusivity, targeting individuals with disabilities by utilizing assistive technologies for improved access to web content. The convergence of the Metaverse and brain-computer interfaces promises to seamlessly merge virtual experiences with cognitive capabilities, offering broad advances in human-computer interaction. The Metaverse is growing financially, indicating a potential investment opportunity beyond the hype. By 2030, the market size of Metaverse is expected to reach 936.57 billion US dollars [4].

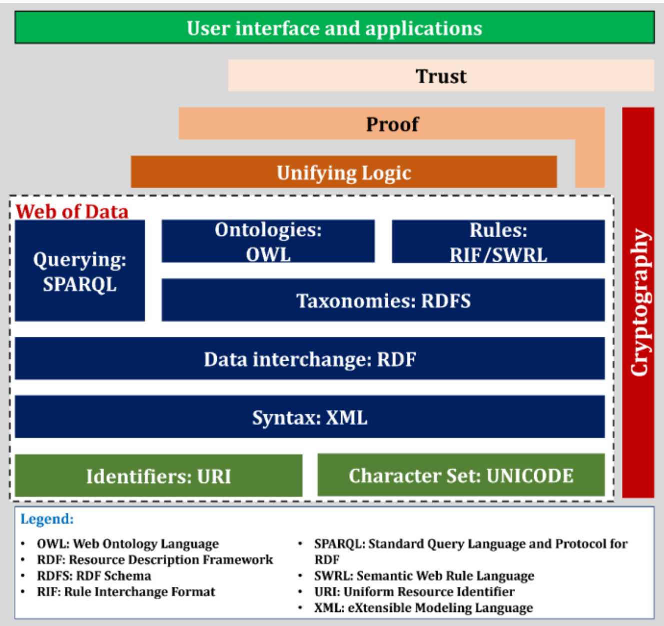

Figure 3: Web 3.0 stacked layer architecture (Adapted from [19])

4.1. Significance of Metaverse and Web 4.0 to Industrial Ecosystem

The EU predicts that digitalization [5], specifically with the emergence of Web 4.0, will play a significant role in driving the economy beyond 2030 [6]. The virtual worlds market is expected to grow substantially, but with both opportunities and challenges that require attention. To align Web 4.0 and the Metaverse with EU values and principles, the EU has developed a strategy that focuses on skills, business, public services, and global governance. The pillars of the strategy include empowering people, supporting a European Web 4.0 industrial ecosystem, supporting societal progress and virtual public services, and shaping global standards [7]. This technology can revolutionize Industry 5.0 by allowing individuals to shape and personalize value creation within the industrial landscape. The four critical pillars for strategy, which aim to strengthen people's abilities and skills, foster a European Web 4.0 industrial ecosystem, support societal progress and virtual public services, and form global standards for open and interoperable virtual worlds and Web 4.0. Furthermore, this section explores how the Web 4.0-based industrial Metaverse can transform Industry 5.0 by providing individuals with the power to shape and customize value creation within the industrial landscape based on human-centred innovation and cutting-edge technology.

4.2. Metaverse & Industrial Metaverse

Metaverse

1. The Metaverse concept in "Snow crash" involves a virtual realm that can be accessed by individuals through specific equipment, allowing them to take on an avatar identity [8]
2. According to Britannica, the Metaverse is a proposed network of immersive online worlds experienced through virtual or augmented reality, where users can interact with each other, buy goods and services, and access unique items solely available in the virtual world. It is seen as the next step in the evolution of the internet beyond social media and smartphone applications [9]
3. Meta describes the Metaverse as the forthcoming advancement in social connectivity, superseding the era of mobile internet [10]
4. A network of 3D virtual environments, the Metaverse concentrates on social interaction and financial engagement [11]

Industrial Metaverse

1. According to Nokia, the industrial metaverse integrates physical and digital elements, along with human enhancements, to provide practical applications within industrial settings. It consists of digital representations of physical industrial spaces, systems, assets, and environments. This technology allows individuals to manage, communicate, and engage with these representations [12].
2. The Industrial Metaverse involves a structured approach that employs hardware such as sensors and VR headsets, data analysis using machine learning to convert information into valuable insights, cyber infrastructure for managing time histories, and human-machine interfaces that enable cognition. It utilizes the Metaverse Ecosystem to facilitate configuration. Integrating the Industrial Metaverse into existing manufacturing systems offers numerous benefits, including reduced scrap and rework, decreased unscheduled downtime, lower compliance costs, increased throughput, and enhanced training [13].

5. Metaverse Challenges

This Section provides an overview of the challenges facing the Industrial Metaverse as evidenced in the literature. This technology has a significant impact on society and government, presenting both advantages and drawbacks. Some of the challenges include virtual collaboration, training, remote maintenance, supply chain management, health concerns, and cyber threats, among others. Addressing these issues is crucial to effectively integrating the Industrial Metaverse into our lives while ensuring that it benefits individuals and society.

The Metaverse also has significant implications for government and society, such as digitalizing public services, facilitating virtual town halls, collaborative policy-making processes, transparency, and accountability, among others. Inclusivity in the Metaverse is also essential as it allows diverse individuals to participate effectively in governance processes. This feature leads to more effective and responsive governance in the digital age [14].

Additionally, the integration of Society 5.0 principles with the Metaverse presents exciting research opportunities. These endeavors raise questions about how the Metaverse can facilitate Society 5.0's principles in diverse domains, where virtual technologies such as AI, VR, AR, and blockchain foster a cognitive and creative society. These developments have transformative potential in fields such as training, education, healthcare, and supply chain management [15]. For instance, virtual healthcare helpers that utilize VR, cloud, and 5G technologies can be created. Researchers exploring these intersections can unlock Metaverse's full potential in shaping Society 5.0's human-centered and technology-driven vision for future generations [16]. Thus, as the Metaverse originated from humans, the principle of prioritizing human operators and users should be followed.

Finally, Metaverse will be called to deal with substantial cybersecurity challenges. Threats in the industrial Metaverse are no different from the threats we face today on the Internet, as the authors in [23] highlight, security threats are of great concern. Virtual Reality systems utilize the users' biometric data which makes them susceptible to numerous attacks such as zero-effort attacks, statistical attacks, and credential-aware attacks. Furthermore, Deepfake attacks pose significant risks through face swapping, lip-syncing, and visual speaker authentication techniques. Also, Augmented Reality systems hold a lot of information about the user's biometric data which makes such systems also vulnerable to privacy data attacks with mimicking (impersonation) methods. The authors in [24] give four characteristics (Socialization, Immersive, Real world-building, Expandability) which are the benefits that Metaverse offers, but at the same time are suffering from privacy and security risks. Injection attacks, Cross-site scripting, Privacy leakage, Sensory data leakage, Biometrics leakage, Third-party tracking, Cross-app tracking, Data security and privacy in digital twins are among the few security and privacy issues the author's mention.

6. Technical framework for the industrial Metaverse

In 2020, spatial computing experienced a significant shift, with software platforms playing a crucial role in facilitating the creation and execution of application programs [18]. However, published works discussing the complications of software platforms in the context of the Metaverse are limited. One such study is based on XR software platforms designed for the Metaverse [19]. This study identifies five layers: a) enabling, b) content, c) human-centered, d) utility, and e) application platforms (Figure 4). These layers comprise various components [20]:

- **Enabling Platforms:** serves as the fundamental architecture of the Metaverse ecosystem
- **Content Platforms:** facilitates the creation, distribution, and consumption of diverse digital content
- **Human-Centered Platforms:** emphasizes user interaction and experience to create a user-centric and immersive digital environment

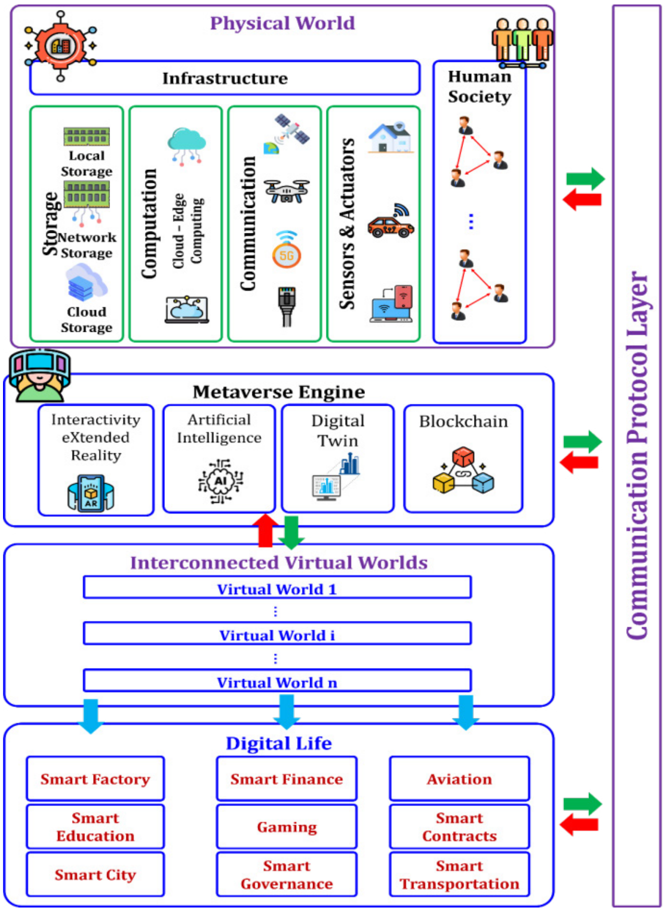

Figure 4: Technical framework for the industrial Metaverse (Adapted from [19])

- **Utility Platforms:** integrates IoT devices and protocols to enable real-time data acquisition and communication
- **Platforms for Applications:** provides a canvas for developing and executing various application scenarios
- **Communication Protocols Layer:** ensures seamless and secure data exchange between IoT devices, smart sensors, immersive interfaces, and backend systems using standardized communication protocols such as Message

Queuing Telemetry Transport (MQTT) and Constrained Application Protocol (CoAP).

6.1. Applications of Industrial Metaverse in Industry 4.0 applications and beyond

The Metaverse uses eXtended Reality (XR) technologies to enhance virtual classrooms through immersive experiences, such as exploring the human body. Online platforms like Zoom and Teams play significant roles in virtual classrooms, enabling remote teaching. The Metaverse employs augmented reality and other technologies to make learning more engaging, convenient, and comprehensive. Learners have increased opportunities to experience, explore, learn, teach, collaborate, and interact with others. Thus, Figure 5 presents an Edu-Metaverse Framework for Product Service System (PSS) Collaborative Assembly.

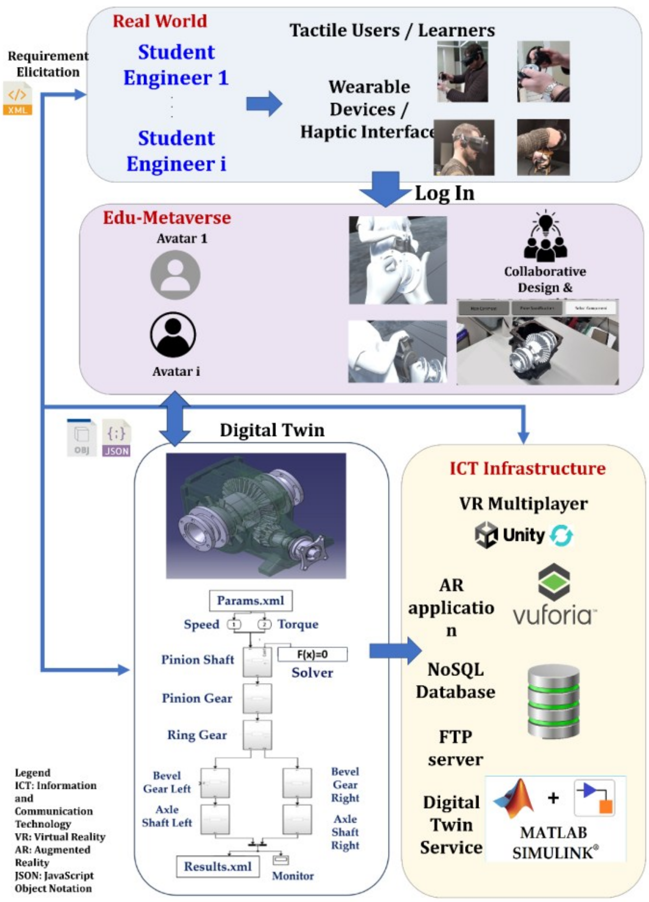

Figure 5 - The Edu-Metaverse framework for product–service system (PSS) collaborative assembly (Adapted from [19])

Consequently, Metaverse has expanded and in other areas such as clinical medicine [25] where through virtual platforms [26] healthcare practitioners monitor patients' health [27] which facilitates the interaction between them. Metaverse comes to bridge the gap between patients and healthcare providers giving continuous care and personalized treatments. In this way Metaverse could help urban decentralization and still allow access to critical services for the wellness of humanity. For example, the public sector could be fully digitalized bringing innovative services to the citizens, more transparent and efficient [28].

7. Conclusions

This work attempted to recognize, analyze, and quote the challenges and the opportunities that come with the growth of industrial metaverse. We highlight the transformative potential of the industrial metaverse in driving a shift from Industry 4.0 to Industry 5.0, where human-centered technology is prioritized. By integrating digital twins, blockchain, and 5G/6G communications, the metaverse enables improved human-machine interactions, enhances operational efficiencies, and provides immersive environments for industrial applications. This evolution supports a more resilient, sustainable industrial landscape that fosters collaboration and enhances the user experience through real-time data and advanced computing.

We also discuss Web 4.0 as a critical framework in expanding the reach and functionality of the metaverse. By emphasizing interoperability, inclusivity, and global governance, Web 4.0 connects diverse devices and users, facilitating a seamless interaction between physical and digital worlds. The European Union's strategy aligns Web 4.0 with digital transformation goals, focusing on empowering people, supporting business growth, and promoting transparency. This foundational layer enables industries to personalize value creation and drive sustainable digital innovation.

The document underscores various challenges that accompany the industrial metaverse's integration into modern industries. Key issues include data privacy risks, cybersecurity threats, and the complexities of maintaining real-time synchronization between digital and physical systems. As virtual and augmented reality applications grow, concerns about biometric data security, susceptibility to attacks (like deepfakes), and cross-platform privacy violations become increasingly significant. Addressing these challenges is essential for ensuring that the metaverse can be securely and effectively utilized in industrial settings, enhancing trust and safeguarding both user and system data in a rapidly evolving digital environment.

Finally, we explore numerous applications of the industrial metaverse, extending across fields like manufacturing, healthcare, and education. In manufacturing, digital twins and augmented reality enable real-time monitoring, predictive maintenance, and optimized workflow management, reducing operational costs and downtime. In healthcare, metaverse technologies support remote diagnostics and personalized treatment by creating virtual environments for doctor-patient interaction, even in decentralized locations. Additionally, the metaverse enhances education through immersive learning experiences, where students and professionals can engage in hands-on virtual simulations. These applications illustrate how the industrial metaverse serves as a versatile tool for enhancing efficiency, accessibility, and innovation in various sectors.

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