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Review

Computer vision meets metaverse

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Abstract: This comprehensive analysis delves into the historical progression and important technological and contemporary advancements of computer vision inside the metaverse. The metaverse, which can be characterized as an interactive virtual reality environment that mirrors the physical world, signifies a novel domain for the utilization of computer vision in various applications. These applications span from object identification and tracking to gesture recognition and augmented reality. Additionally, a thorough evaluation of specific case studies occurs to provide a deeper understanding of the subject. Despite notable progress, the incorporation and utilization of computer vision inside the metaverse present numerous obstacles, including computational expenses, apprehensions regarding data privacy, and the faithful replication of physical aspects of reality. Potential solutions are examined, including deep learning approaches, optimization strategies, and the formation of ethical guidelines. A comprehensive analysis of anticipated patterns within the industry is also included, with emphasis on the confluence of artificial intelligence, the Internet of Things, and blockchain technologies. These convergences are predicted to create substantial prospects for the advancement of the metaverse. This review culminates by offering a contemplation on the ethical considerations and duties that arise from the utilization of computer vision in the realm beyond mortal existence. Research findings demonstrate that these technologies have greatly augmented user engagement and immersion within the digital domain. Readers can enhance their understanding of the interdependent connection between computer vision and the metaverse through the present analysis of existing scholarly works. Thus, this study aspires to make a valuable contribution to the advancement of research in this new domain.

Keywords: computer vision; metaverse; visual world; IoT; blockchain; artificial intelligence

1. Introduction

The notions of computer vision and the metaverse play a crucial role in facilitating a paradigm shift in digital interaction and perception [1,2]. Computer vision (CV) is a multidisciplinary domain that integrates principles from computer science, artificial intelligence (AI), and image processing [3] to facilitate the ability of machines to comprehend and interpret visual information. According to Xi et al. [4], the concept of the metaverse, in contrast, refers to a collaborative virtual environment that encompasses both augmented reality and virtual reality, achieved through the interconnectedness of computer networks. Based on Kim et al. [5], both of these domains have had notable advancements, characterized by substantial contributions from their respective technologies and applications in recent times. Moreover, Zhang et al. [6] stated that the convergence of computer vision with the metaverse presents novel opportunities for virtual interactions and experiences, including the development of more immersive environments, the enhancement of the user experience, and the bolstering of security measures.

The scope of this bibliographic study is to examine existing material pertaining to the installation and utilization of computer vision technology within the metaverse. This study aims to provide a comprehensive exploration of the historical progression of these disciplines, the identification of pivotal technologies and methodologies, a thorough examination of contemporary applications, and the presentation of notable case studies. Furthermore, this work examines the difficulties encountered during the integration of computer vision into the post-sight process, as well as the suggested remedies. Additionally, potential future developments, opportunities, and ethical implications are discussed. The significance of doing this critical analysis lies in its ability to facilitate comprehension of the changing dynamics between computer vision and the metaverse. This analysis aims to offer valuable insights to researchers, developers, and avid users who are actively creating the future of these interrelated domains. Existing obstacles associated with the integration of the Internet of Things (IoT) and blockchain technologies within the context of the metaverse domain are also examined. Additionally, possible benefits that may derive from the synergistic utilization of these two technologies are also highlighted. To this end, it is anticipated that the thorough synthesis of information drawn from the literature will serve as catalysts for additional innovation and study on this significant subject [7].

Therefore, the primary contributions of this study can be summarized as follows:

- The delivery of a comprehensive survey on computer vision techniques in the metaverse, focusing on its distinctive characteristics and identifying the key issues that it is currently facing;
- The identification and examination of various methods for integrating computer vision in the metaverse.

The rest of the paper is structured as follows: Section 2 presents the review methodology followed in this work. Section 3 provides a comprehensive historical overview of computer vision and the metaverse ecosystem. Section 4 investigates the fundamental technologies and techniques employed both in computer vision and the metaverse. Section 5 provides an overview of the current state of computer vision in the metaverse, including a comprehensive description of case studies. Section 6 provides an overview of the difficulties and solutions related to computer vision in the metaverse, as well as potential future trends and opportunities, and provides a comprehensive analysis of ethical considerations related to the subject. Finally, the paper concludes with the results and suggestions for further research, discussed in Section 7.

2. Review methodology

The review methodology followed in this work is in line with the principles provided by Kitchenham [8]. All research was implemented in the Scopus database, by inserting the following search query within the article title, abstract and keywords: "(computer vision) AND (metaverse)". This first search rule indicated 118 documents.

In the following, eligibility criteria were selected; first, computer vision and metaverse terms had to be included in the keywords of all documents; only documents written in English were eligible (94 documents); all documents need to be at a final published stage; all documents must be relevant to the subject of computer science. Filtering regarding the year range was not applied since the metaverse is a relatively newly introduced concept. At the final screening step, all documents were checked regarding their relevancy to the subject.

Figure 1 illustrates the steps of the conducted research methodology. Finally, a set of 68 documents was considered and carefully processed to include their valuable insights in the current review. **Figure 2** shows the number of publications on the subject per year, based on the set of the final selected publications. While the term metaverse was first reported in 2011, the volume of research work is located mainly in the two previous years, 2022 (26 documents) and 2023 (37 documents), indicating a growing research interest in the topic.

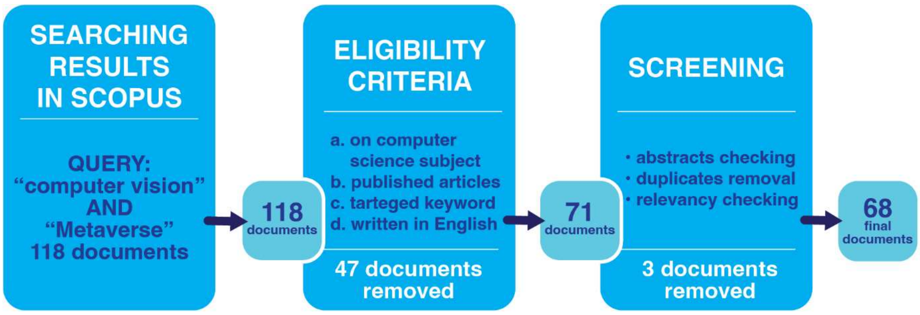

Figure 1. The flow of the selected research methodology.

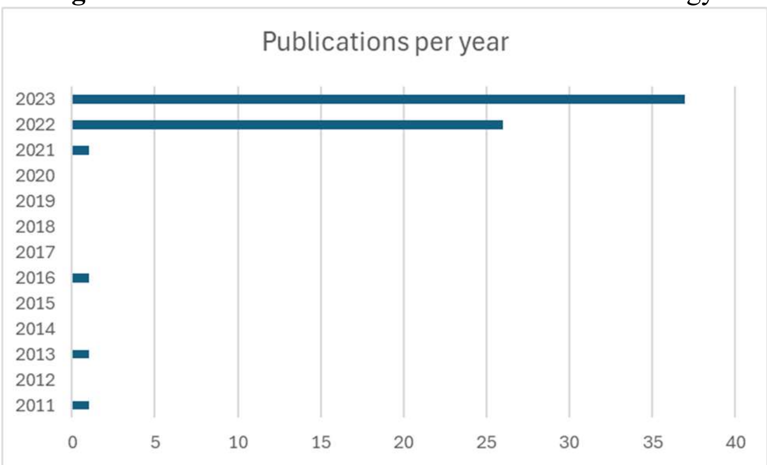

Figure 2. Publications per year.

3. Historical overview

The historical development of computer vision is closely linked to the advancements in AI and computer science, stemming from the aspiration to endow machines with a visual comprehension akin to that of humans [9].

The origins of computer vision may be traced back to the 1960s when significant advancements were made through groundbreaking research undertaken at many universities and research institutions. The advancement of computer vision had been incremental until the recent emergence and incorporation of machine learning methodologies. The introduction of deep learning in the late 2000s and its subsequent implementation in computer vision applications led to a significant enhancement of the capabilities of this discipline [10]. Advancements in sequential neural networks, image identification, and object detection have led to increased accuracy, marking the beginning of a new era in the realm of practical applications.

Simultaneously, the genesis of the metaverse can be traced back to the realm of science fiction, primarily credited to Neal Stephenson's 1992 literary work entitled

"Snow Crash" [11]. Within this novel, Stephenson envisioned the metaverse as a prospective evolution of the Internet, built upon virtual reality foundations. Nonetheless, the practical application of this concept remained speculative until advancements in technology facilitated the development of immersive virtual environments. In the study by Tsou and Mejia [12], the proliferation of Augmented Reality (AR), Virtual Reality (VR), and Mixed Reality (MR) technology in recent times has resulted in the metaverse transitioning from speculative imagination to impending actuality. According to The et al. [13], the integration of computer vision and metaverse has exhibited a growing level of dynamism. The integration of AI and AR/VR technologies has led to the prominence of computer vision as a crucial element in the creation of immersive, interactive, and intelligent settings within the metaverse [14,15]. The convergence of this particular domain has been of utmost significance in various domains, including user engagement, content generation, and safeguarding measures [16].

The initial instances of the convergence of computer vision and metaverse were primarily experimental in nature and predominantly confined to research facilities. In recent years, there has been a notable transition from experimental to practical applications, especially during the past decade. These applications involve a wide range of fields, including virtual gaming, social platforms, education [17,18], healthcare [19,20], and corporate collaborations [21]. As stated in the study by Sharma and Choudhury [22], the aforementioned applications have utilized computer vision capabilities, including gesture recognition, facial expression analysis, and object detection, in order to provide enhanced virtual experiences.

A specific use case where computer vision has demonstrated notable success in these fields is provided in the study by Tiwari et al. [23]. The authors used computer vision to detect QR codes with smart glasses, so as to generate details of the scanned codes in real-time. Smart glasses are a game-changer technology for metaverse applications since embedded displays on the glasses are able to provide a wide range of possibilities to the users, from facial recognition to the design of virtual worlds. Note that recently, Meta smart glasses in collaboration with Ray-Ban, launched smart glasses with enhanced audio and visual capabilities, also integrating GTP-4 to provide audio information to people with visual impairments, by processing text images i.e., from restaurant menus [24]. Jiang et al. [25] presented a vision-enhanced wireless device tracking system with high accuracy, aiming to provide a valuable technological tool for industry, health care, food industry and more, where intuitive operation on devices connected to the internet is required. Yang et al. [26] introduced a device-free human pose estimation scheme for metaverse avatar simulation. In general, pose estimation is based on cameras equipped with computer vision algorithms that enable avatar digitization. Similar to pose estimation, facial landmarks prediction is a specific use case to make metaverse characters look more realistic. Han et al. [27] develop facial landmarks prediction for audio-driven lip movement designated for metaverse avatars. Song et al. [28] presented an approach for real-time avatar body generation, that uses computer vision to update texture and normal map commulatively. The integration of Brain-Computer Interface (BCI) technologies with metaverse is another application field of computer vision that opens numerous possibilities [29].

In order to comprehend the potential contribution of computer vision in all aforementioned fields, it is imperative to acknowledge their collective historical evolution. The accelerated progress and extensive utilization of computer vision within the framework of the post-scenic era suggest an ongoing trajectory that needs thorough examination and comprehension [30]. By employing this approach, researchers could be able to discern areas of deficiency and potential avenues for exploration, thus influencing the trajectory of forthcoming research endeavours and practical implementations.

4. Basic computer vision and metaverse techniques

Computer vision is a multidisciplinary area of research that aims to enable robots to comprehend and interpret visual information within their surroundings [31]. Over time, this area has experienced substantial growth, characterized by notable advancements in pivotal technologies and methodologies such as image recognition, object detection, segmentation, and tracking.

Image recognition, which is often referred to as image classification, encompasses the process of instructing computer systems to identify and classify various components included in an image [32]. The typical approach involves the utilization of neural synergistic learning networks such as convolutional neural networks (CNNs), which are a kind of deep learning models specifically built to autonomously acquire and adjust spatial characteristic hierarchies based on training data. Based on the study by Rawat and Wang [33], the architecture of CNNs enables them to effectively process the complex and high-dimensional nature of raw images, resulting in notable enhancements in recognition accuracy.

The scope of object detection includes more than just picture recognition, as it involves the identification and monitoring of many things inside an image. In this topic, two prominent ways are widely utilized. The first approach involves the use of two-stage detectors, such as the region-based CNNs (R-CNNs). The second approach involves the use of one-step detection devices, such as You Only Look Once (YOLO) and Single Shot MultiBox Detector (SSDs) [34]. These techniques have demonstrated significant value in a range of applications, including autonomous driving, video monitoring, and facial recognition systems.

Segmentation, a crucial task in the field of computer vision, involves the partitioning of a picture into numerous distinct regions, also known as superpixels. Semantic segmentation, as an illustrative instance, endeavours to assign a label to every individual pixel within an image, hence facilitating accurate identification and delineation of objects and their respective borders. The utilization of fully connected networks (FCNs) and U-Net techniques has demonstrated notable enhancements in the outcomes of this task [35].

Monitoring, a crucial aspect for the observation and recording of object trajectories over some time, plays a pivotal role in numerous domains, including but not limited to video surveillance, human-computer interaction, and sports analysis. One of the main difficulties in the field of tracking is accurately determining objects that undergo significant changes in their appearance. This difficulty is frequently addressed through the utilization of sophisticated algorithms, such as the Multiple Object Tracking (MOT) framework.

The evaluation of the performance of these basic computer vision techniques within the metaverse is implemented by using well-known evaluation metrics. In general, performance evaluation includes measuring the basic behaviours of the computer vision algorithms for specific tasks. Different metrics are therefore used based on each computer vision-based task: accuracy, precision, recall, F1-score, intersection over union (IoU), mean average precision (mAP), root mean square error (RMSE), and more. Speed is an additional metric referring to the time taken by the computer vision model to process an image or video frame. Speed is considered important in real-time applications, such as those implemented in the frame of the metaverse. Therefore, in metaverse, the processing speed of computer vision algorithms may be more important than accuracy in real-time applications, while in other cases, accuracy may be the primary concern. The selection of the appropriate metric depends on the objectives of each task and the characteristics of the data as well as the model being used [36].

As stated by Nilsson et al. [36], in recent years, machine learning techniques, particularly deep learning, have undergone substantial advancements. Advancements in technology have endowed computer vision with the capability to determine sophisticated patterns and obtain knowledge from them. Furthermore, AI assumes a crucial function in improving these methodologies, enabling them to acquire knowledge, enhance performance, and adjust accordingly, to optimize their precision and dependability [37,38].

Saffo et al. [39] suggest that social VR platforms have the potential to facilitate Human-Computer Interaction (HCI) evaluations. These platforms enable researchers to execute collaborative VR experiments, wherein experimenters and participants can engage in synchronous virtual environments from remote locations [40]. This eliminates the need for complex application distribution and networking implementations, thereby streamlining the evaluation process. The researchers of this study conducted two user studies utilizing VRChat, a virtual reality platform designed for social interaction. Through their investigation, they effectively showcased the feasibility, reliability, and ethical considerations associated with conducting user studies inside a social virtual reality environment. In addition, Saffo et al. [39] offer implementation specifics and openly accessible resources concerning these investigations. Furthermore, they provide suggestions to assist future researchers in adopting their methodology, with a special emphasis on the utilization of VRChat.

The implementation of *gamification* inside the metaverse has the potential to cultivate an immersive and captivating environment, hence exerting a favourable impact on users' perspective towards social interaction [41]. The inclusion of gamified aspects inside the metaverse has the potential to elicit a heightened sense of enthusiasm among users, thus, facilitating the expression of their mood and emotion. Tayal et al. [42] have conducted a study in which they detected the utilization of game features in various systems and the resulting impact on user behaviour.

Mystakidis [43] examines the metaverse as a forthcoming pervasive computer paradigm with the capacity to revolutionize diverse sectors such as education, business, distant employment, and entertainment. Spatial computing is a fundamental technological component that facilitates the realization of the metaverse. Spatial computing is a technological approach that involves the utilization of sensors, algorithms, and displays to generate interactive and immersive encounters that seamlessly integrate physical and digital surroundings. Spatial computing, under the framework of the metaverse, facilitates users' engagement with virtual environments through the use of gestures, voice commands, and several other input methods, hence enabling a seamless and instinctive interaction experience. As claimed in the study by Mystakidis [43], the utilization of multisensory interactions with virtual objects and avatars facilitates the establishment of a perceptual experience and deep engagement that is crucial for the metaverse encounter.

Haptic feedback plays a crucial role in increasing the immersive nature of the metaverse. Haptic feedback can replicate the tactile experiences of users in virtual environments through the use of vibrations or alterations in temperature, thereby creating a sense of interaction with virtual things. The latter has the potential to augment the user's perception of the environment and imbue the experience with a heightened sense of realism. The study conducted by Sun et al. [44] presents an illustration of the potential integration of haptic feedback into wearable devices, namely through the development of augmented tactile perception and haptic feedback rings. This integration aims to enhance the overall perception and feedback encountered within the metaverse.

Cao [45] discusses the potential for enhancing the metaverse through recent advancements in different research domains, such as Decentralized AI (DeAI), cloud and edge computing, blockchain, and Decentralized Identity (DID). Decentralized identification refers to a form of digital identification wherein individuals possess and exercise full ownership and control over their identity, as opposed to being under the ownership and control of a centralized authority. Within the framework of the metaverse, the utilization of DID can facilitate the establishment of an enduring and transferable identity for users. This identity can be seamlessly employed across many virtual realms and applications, hence eliminating the need for dependence on a centralized body responsible for identity provision [46,47]. The use of this approach has the potential to improve privacy, security, and interoperability inside the metaverse [45].

Cross-platform integration within the metaverse refers to the establishment of a cohesive framework that enables smooth interoperability and interaction across diverse virtual environments, applications, and platforms. In their study, Chen et al. [48], presented a thorough examination of the aforementioned process, with particular emphasis on the standardization of protocols, the establishment of asset compatibility across various platforms, the implementation of Single Sign-On (SSO) and decentralized identity systems, and the facilitation of cross-platform communication. The establishment of standardized protocols and communication methods plays a critical role in promoting interoperability and facilitating smooth communication. Open Application Programming Interfaces (APIs) facilitate the creation of cross-platform apps and services by developers. The uniformity of the user experience relies heavily on the compatibility of assets across different platforms. The implementation of SSO and decentralized identity solutions has the potential to augment security measures and safeguard privacy. In summary, the objective of cross-platform integration is to eliminate segregated divisions within the metaverse, enabling individuals to enter and interact with a unified and interconnected digital realm.

Communication standards play a crucial role in enabling the sharing of information and fostering interpersonal relationships across various platforms. The efficiency of cross-platform integration relies on the imperative nature of collaboration among platform suppliers. Standards for user data portability aim to provide a cohesive identity and uniform user experience across various metaverse environments.

The significance of Lo and Tsai's cognitive theory of multimedia learning (CTML) in the design of 3D virtual reality for environmental conservation education has been established by their research conducted in 2022 [49]. The utilization of CTML in multimedia content has the capacity to provide additional potential explanations, hence augmenting learners' comprehension and retention of the material. Hence, it is imperative to incorporate the cognitive theory of multimedia learning while designing the interface through which users interact with and observe content within the simulation environment [50].

The development and interplay of these technologies and methodologies have established the fundamental basis for the effective utilization of computer vision in diverse domains, such as the metaverse [51]. The future potential of computer vision inside the metaverse is heavily reliant on the ongoing innovation and refinement of these technologies. Consequently, it is crucial to explore and comprehend these technologies in order to drive progress in the area. **Table 1** includes a summary of the key metaverse strategies of substantial importance.

Table 1. Review list of substantial metaverse techniques.

Technique	Description
Virtual reality (VR)	Immersive technology that creates a simulated environment, often using headsets and motion tracking, allows users to interact with a computer-generated 3D environment.
Augmented reality (AR)	Overlays digital information into the real world, enhancing the user's perception of their environment through devices like smartphones or AR glasses.
Blockchain	Distributed ledger technology that provides secure and transparent transactions, enabling digital asset ownership and verifiable transactions within the metaverse.
3D graphics	Rendering realistic and interactive 3D visuals to create immersive virtual environments, often used in conjunction with VR and AR technologies.
Spatial computing	Integrates physical and digital spaces, allowing digital objects to interact with the physical world, enhancing the user experience in mixed reality environments.
Artificial intelligence (AI)	Enables intelligent agents, NPCs, and dynamic content generation, enhancing the realism and interactivity of the metaverse by simulating human-like behaviour.
Haptic feedback	Technology that provides tactile sensations to users, allowing them to feel and interact with virtual objects, enhancing the sense of presence in virtual environments.
Decentralized identity	Ensures user privacy and security by allowing individuals to control their digital identity and assets, reducing the risk of centralized control in the metaverse.
Social VR platforms	Facilitating social interactions through avatars and shared virtual spaces, creating a sense of community within the metaverse.
Gamification	Applying game elements, such as rewards and achievements, to non-game contexts within the metaverse to enhance engagement and motivation.
Cross-platform integration	Ensuring compatibility and seamless interaction between different metaverse platforms, allowing users to access content across various environments.

Figure 3 illustrates the system architecture of the metaverse. Its architecture includes seven layers. The base of all layers is infrastructure, without which none of the following developments can be implemented. Therefore, suitable frameworks and technological processes are at the center of metaverse. The next layers comprise

experience, discovery, creator economy, spatial computing, decentralization, and human interface. As it can be concluded from the figure, computer vision is one of the technologies that the metaverse relies on. Computer vision and AI algorithms are employed to render interpretable interfaces towards making the VR/AR/MR experience feel real. Therefore, computer vision is incorporated in the metaverse, in the "Human interface" layer, to help devices interpret how humans interact with their environments and use that information to design hyper-realistic sensory experiences. More details about all layers can be found in the figure (**Figure 3**).

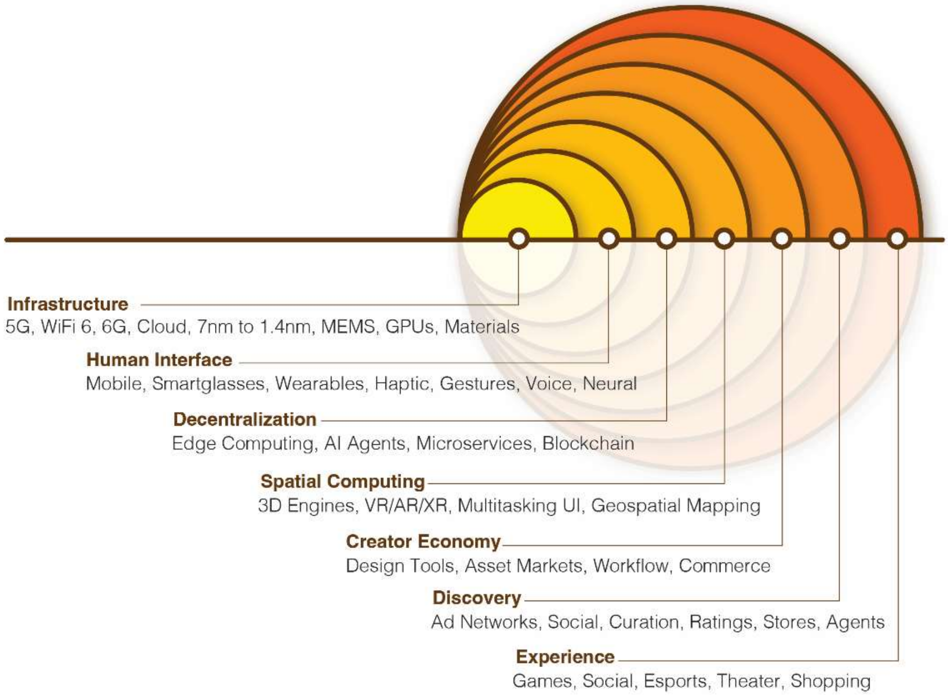

Figure 3. The seven layers of the metaverse.

5. Computer vision in the metaverse

The present utilization of computer vision in metaverse is vast and comprehensive, providing substantial support to several fundamental components, encompassing user engagement, content generation, environmental comprehension, and security.

The extent of user engagement in the afterlife is heavily reliant on computer vision technology. Sharma and Choudhury [22] emphasize the significance of gesture recognition, facial recognition, and eye monitoring within the domain of this field. Gesture recognition involves the identification and comprehension of human gestures by a computer device. This technology enables users to engage with the metaverse in a manner that is both instinctive and authentic, hence augmenting the level of immersion experienced. The importance of this technology has grown significantly in various contexts, spanning from basic point-and-click applications to intricate manipulation of objects within virtual environments.

The field of facial expression recognition, which is a fundamental aspect of emotional computing, focuses on the identification and interpretation of human emotions based on facial expressions [52]. The utilization of metaverse technology facilitates the augmentation of social relationships through the acquisition and representation of users' emotional states within their virtual avatars [53]. This feature enhances the self-presentation within the metaverse by enabling more vibrant and expressive avatar-based communication.

Eye tracking, a fundamental component of user interaction, is the identification and differentiation of the specific direction in which a user's gaze is focused. Jang [54] claims that the analysis of user behaviour, attention, and engagement inside the virtual environment might yield valuable insights. Eye tracking technology not only offers insights into users' interests but also contributes to the development of immersive and tailored experiences by detecting and responding to users' visual attention within the metaverse.

The utilization of computer vision technology within the metaverse greatly enhances content development, particularly in procedural content generation. The utilization of algorithms in this methodology significantly diminishes the need for manual labour in the creation of textures, soils, and entire worlds [55]. The integration of computer vision techniques with this approach has the potential to enhance the precision and authenticity of virtual worlds by leveraging real-world photographs. Furthermore, computer vision assumes a pivotal function in augmenting the quality of AR and VR encounters within the metaverse, guaranteeing precise alignment of virtual entities with real-world surroundings or constructing entirely immersive virtual worlds [56].

Computer vision plays a crucial role in augmenting the understanding of the surroundings; hence it serves as a significant application. By employing methodologies such as object recognition, depth detection, and scene reconstruction, the virtual environment is capable of generating realistic responses to user activities [57,58]. The process of object recognition plays a crucial role in facilitating the metaverse's ability to understand and respond to particular objects that have been imported by users. This capability contributes to the creation of an environment that is characterized by its adaptability and fluidity. In contrast, depth detection and scene reconstruction techniques offer a precise and three-dimensional depiction of the virtual environment, enhancing the overall user experience [59].

Moreover, computer vision plays a crucial role in augmenting *security* and *privacy* measures within the metaverse. The utilization of biometric identification technologies, like as facial recognition and iris scanning, has witnessed a growing trend in their application for user authentication within the metaverse. This implementation serves the purpose of safeguarding the security of users' accounts and personal data. The utilization of computer vision in the metaverse contributes to the preservation of content by employing algorithms that possess the ability to identify and eliminate improper material. Consequently, this facilitates the establishment of virtual environments that are safer and respectful [60].

The aforementioned areas of focus serve as a glimpse into the present and future possibilities of computer vision within the metaverse. It is crucial to realize that this particular industry is undergoing rapid development, and these applications are anticipated to grow and develop alongside technology advancements and the growing acceptance of the metaverse. Computer vision plays a crucial role in the metaverse, offering enhanced immersion, improved interactivity, and heightened security. This field of research and development remains captivating and holds significant potential.

Case studies

The examination of certain instances where computer vision is applied within the metaverse yields significant insights into the profound impact of this technology. Numerous case studies provide evidence of the efficacy of computer vision in enabling diverse, engaging, and secure experiences in the absence of visual perception [61].

A notable illustration of the use of computer vision in the metaverse can be observed within the realm of VR social platforms, exemplified by Facebook's Horizon Workrooms [62] (**Figure 4**). The use of computer vision technology on this platform enhances the efficacy of remote working by providing seamless communication and cooperation inside a virtual setting. Horizon Workrooms utilize gesture detection technology to enable users to engage in an intuitive interaction with the virtual world. This technology enables users to manipulate virtual objects and interfaces with greater intuitiveness compared to conventional keyboard and mouse interactions, by interpreting hand gestures. Furthermore, facial recognition methods employed by the platform capture and analyze users' facial expressions, subsequently comparing them to their corresponding avatars. This process serves to augment the level of non-verbal communication experienced within the virtual environment. The incorporation of this technology enhances the authenticity and emotional subtlety in communication with avatars, which holds significance within professional settings where subtle non-verbal cues can impact collaborative efforts. Furthermore, the use of eye tracking technology is employed to decipher the user's gaze direction in the simulated environment. This functionality facilitates the perception of the user's focus and engagement, so it enables a communication experience that is more adaptable and interactive. In general, these technologies exemplify the potential of computer vision to enhance distant collaboration in the metaverse, offering a heightened level of immersion and interactivity in contrast to conventional videoconferencing methods.

Figure 4. Facebook's horizon workrooms [63].

The use of computer vision in metaverse-based games is well demonstrated in the game Pokemon Go [64] (**Figure 5**). This game entails the engagement of players with virtual creatures that are strategically positioned in real-world settings, delivering an immersive AR experience. Pokemon Go employs a variety of computer vision technologies in order to accomplish this task. The process of object recognition is employed to identify appropriate positions for virtual entities, whilst depth perception guarantees accurate positioning of these entities within the surrounding context. Furthermore, tracking techniques are effectively employed to preserve the spatial alignment of the plasma with respect to the user's motions, ensuring a consistent AR encounter. This case study highlights the significant impact of computer vision in the development of immersive AR experiences that integrate virtual and actual environments.

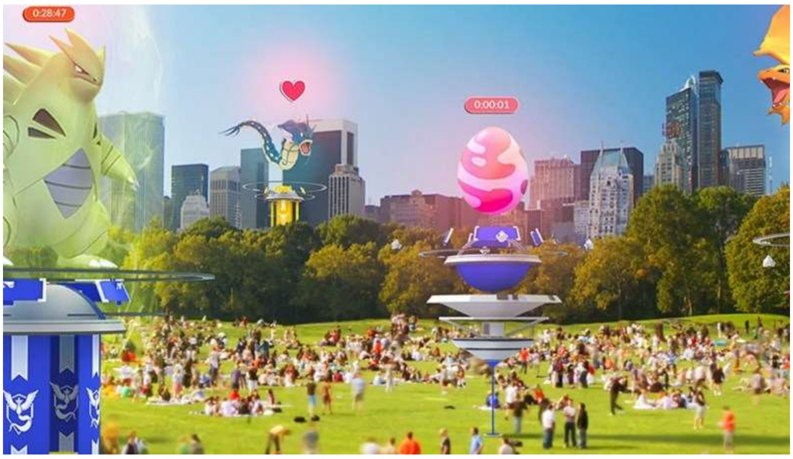

Figure 5. Pokemon go by Niantic [65].

The fashion business presents a noteworthy exemplification of the influence of computer vision in metaverse. Computer vision technology is utilized by retail platforms like Zara and ASOS (**Figure 6**) to establish virtual testing systems [66]. Various techniques, including object detection, segmentation, and posture evaluation, are employed to discern human figures, distinguish clothing from the surrounding background, and precisely align clothing with the human form. The application of computer vision in this context, represents a groundbreaking advancement in the realm of metaverse commerce, offering users a highly immersive and lifelike e-commerce experience.

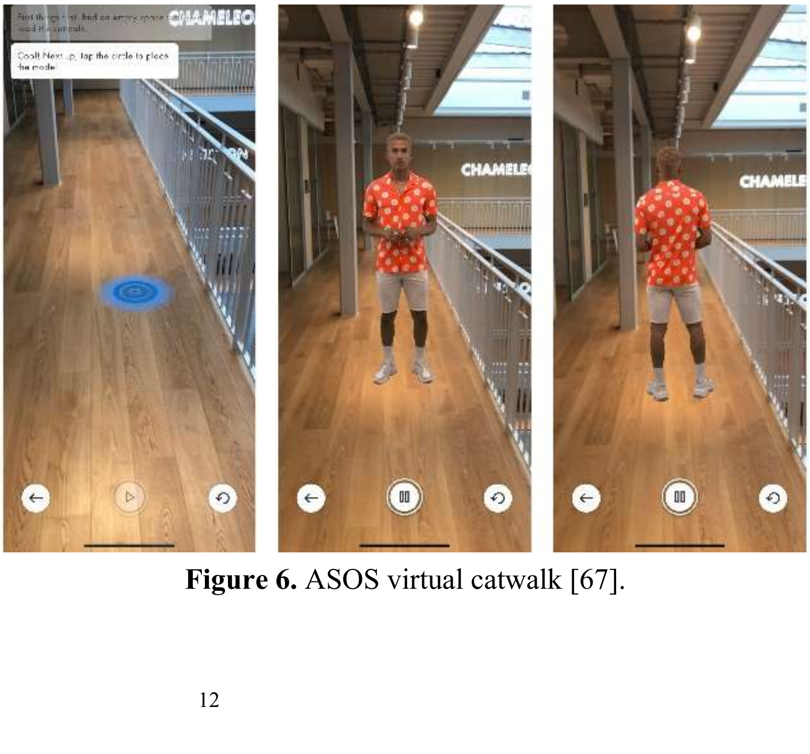

Figure 6. ASOS virtual catwalk [67].

The significance of computer vision in ensuring security within the metaverse is demonstrated through the use of biometric recognition technologies on platforms like Meta's Oculus [68]. The use of facial recognition technology on the Oculus platform serves the purpose of verifying the identity of users during the connection process, thereby mitigating the risk of unlawful entry and bolstering the overall level of security. This case study shows the crucial significance of computer vision in enhancing security measures within the metaverse, a domain of growing significance due to escalating user engagement in virtual environments.

6. Challenges and solutions, future trends, and opportunities

In this work, all extracted findings are based on experts' contributions, referenced within the manuscript. Therefore, reported trends, approaches and results, are captured to deliver the current orientations of research on the subject. This specific aspect is of major importance, since the metaverse is an emerging field, and it is based on evolving technologies; therefore, it is dynamically changing. In the following, related challenges and gaps in the existing literature identified from the bibliography are gathered, so as to deliver the current status of computer vision in the metaverse and provide insights to researchers towards targeted future research directions.

6.1. Challenges and solutions of computer vision in the metaverse

Computer vision holds significant promise for the metaverse, although it also poses distinct issues that necessitate comprehensive and cohesive resolutions. One significant obstacle in the use of computer vision technology in the metaverse is related to privacy [60]. Computer vision in the metaverse raises concerns about privacy and data protection, as it involves capturing and processing large amounts of user data, such as facial expressions, body movements, and voice commands. The increasing use of computer vision systems in gathering and examining substantial quantities of user data, often encompassing personal biometric data, has prompted a rising apprehension regarding potential data exploitation. In light of prominent data breaches in recent years, the importance of resolving privacy concerns has increased due to the rising sensitivity around data privacy. Potential strategies encompass the establishment of robust data protection rules and methods, such as the implementation of data anonymization techniques and the adoption of secure protocols for data storage and transit. Furthermore, the implementation of visible and user-controlled privacy settings can empower users to effectively manage their data and privacy preferences.

One additional obstacle that arises is the potential *presence of bias* inside computer vision systems. According to Buolamwini and Gebru [69], empirical studies have demonstrated that certain computer vision algorithms have the potential to exhibit biases rooted in race, gender, and other variables, hence resulting in outcomes that perpetuate discrimination. To effectively tackle this difficulty, it is imperative to implement a collaborative approach that focuses on mitigating biases present in the data sets utilized for training computational vision algorithms. Furthermore, the enhancement of transparency in the design of algorithms and the decision-making processes might serve as an additional means to alleviate these biases.

The computing demands associated with computer vision systems are also barriers. Numerous computer vision techniques, particularly those involving real-time analysis, necessitate substantial processing resources, hence performance issues arise. One potential approach is the optimization of computer vision algorithms in order to mitigate their processing demands. Furthermore, the utilization of sophisticated hardware accelerators, such as Graphics Processing Units (GPUs), has been shown to enhance the efficiency of computer vision systems within the metaverse [70]. In the latter context, the issue of interoperability also arises. The integration and seamless operation of computer vision systems in diverse situations is crucial inside the metaverse, which involves a range of platforms and technologies. The metaverse is a complex and interconnected system that requires different platforms and devices to work together seamlessly. Computer vision needs to be able to communicate and integrate with other technologies, such as AR, VR, and the Internet of Things. Interoperability can be effectively facilitated by the development of standardized protocols and frameworks.

The dynamic nature of the metaverse presents issues for computer vision systems. The dynamic nature of content and interactions within the metaverse can provide challenges for computer vision algorithms that lack adaptability [71]. Poor data quality due to noise and illuminations, or due to inadequate hardware are barriers. High-quality annotated datasets are needed, as well as high-performance low-cost equipment. Advanced computer vision requires high-quality annotated datasets to inform machine learning models and ensure that metaverse software and hardware can bridge the gaps between the physical and the virtual world. The resolution rests in the development of light, adaptable and flexible models that possess the ability to acquire knowledge and improve their performance over time [72]. This can be achieved by employing methodologies such as online learning and transfer learning [73]. Realism is another related challenge since the metaverse aims to create a realistic and immersive experience for users, which requires computer vision to be able to accurately render and track objects, people, and environments in real-time. Finally, accessibility is another important challenge, since the metaverse must be accessible to everyone, regardless of their physical abilities. Computer vision needs to be able to adapt to users with disabilities, such as visual or hearing impairments, and provide them equally with an inclusive experience [74].

In summary, computer vision possesses significant potential for augmenting the metaverse; nevertheless, it also entails a set of obstacles that necessitate acknowledgement and resolution. Based on the study by Yosinski et al. [75], the effective resolution of these difficulties can be achieved by implementing robust data protection measures, ensuring fairness in algorithmic decision-making, optimizing computing resources, promoting interoperability, and enhancing the adaptability of models. This will serve as the crucial factor in effectively harnessing the capabilities of computer vision in the era following visual perception, hence facilitating the development of immersive, inclusive, and safe virtual environments accessible to all individuals [76]. Ongoing research on computer vision algorithms is expected to play a critical role in making the metaverse a more immersive, accessible, and inclusive experience for everyone.

6.2. Future trends and opportunities

The potential prospects and emerging patterns within computer vision in the metaverse provide a wide range of possibilities, as scholars and experts persistently push the boundaries of this domain through their advancements. One anticipated pattern involves the increased use of sophisticated machine learning methodologies, including deep learning, to enhance the precision and effectiveness of computer vision systems within the metaverse [51]. This phenomenon has the potential to improve user experiences by introducing more intricate avatar expressions and facilitating authentic interactions in the virtual environment [77].

The integration of computer vision with additional sensory input represents a promising direction in the field. Baltrusaitis et al. [78] claim that the integration of visual data with audio, tactile, and other sensory information has the potential to generate multimodal systems that offer enhanced and immersive experiences within the metaverse. The latter has the potential to change the degree to which realism and engagement may be achieved in virtual worlds.

The anticipated growth of AR is significantly influenced, as computer vision assumes a pivotal function in the integration of virtual and physical realities. With the advancement of AR technologies, there is a potential for a rise in metaverse experiences that incorporate “mixed reality” [79]. This refers to the seamless interaction between virtual objects and entities in the physical environment.

The inclusion of user-centered design principles and customizable features within the metaverse presents a compelling prospect for further exploration. The utilization of advanced computer vision algorithms has the potential to enable users to tailor their metaverse encounters in accordance with their individual preferences and requirements. This may encompass personalized avatars, environments, and interactions that are tailored to specific user data [80].

In light of escalating apprehensions regarding privacy and security, forthcoming advancements in computer vision are anticipated to primarily prioritize the safeguarding of individuals in metaverse. This may include the advancement of more secure facial recognition systems or the innovation of novel techniques for anonymizing user data.

To this end, the prospects for computer vision in the metaverse are replete with promising potential and emerging trends. The rapid advancement of technology has the potential to deliver a metaverse experience that is characterized by increased immersion, personalization, and safety.

6.3. Factors that influence the metaverse across different fields

Several factors influence the metaverse across different fields. The most important among them is the environmental impact that may have. On the one hand, by offering virtual experiences the metaverse contributes to the decrease of carbon emissions through the reduction of traveling. On the other hand, the metaverse requires a lot of energy to run, and this energy consumption can have a significant impact on the environment [81]. Moreover, it relies on data centers to store and process information, also affecting the environment.

Another factor that influences the accessibility to metaverse, is due to its *hardware* requirements. The hardware required to run metaverse applications can be expensive and difficult to obtain, which can limit its accessibility. Moreover, the metaverse relies on advanced technologies such as VR/AR, and cloud computing [82] to create immersive virtual worlds. The development of innovative algorithms and the enhancement of these technologies play a significant role in the growth and integration of the metaverse across different fields.

The accessibility of metaverse can also be affected by the *internet connectivity* since it requires a stable and fast internet connection, which can be a challenge in some areas. Finally, some ethical considerations influence the metaverse, related to privacy and security, as described in the following subsection. Ethical considerations need to be handled so as for the metaverse to feel safe and user-friendly. User-adaption is also a factor related to the integration of the metaverse in different fields. If users do not find the metaverse engaging or useful, it will not be successful. Therefore, it is essential to create a metaverse that is user-friendly, intuitive, and provides value to users.

6.4. Ethical considerations

The advancement of computer vision techniques within the metaverse entails several ethical problems and associated duties. The profound data collecting capabilities exhibited by these technologies, particularly when biometric data is implicated, give rise to significant apprehensions over privacy. It is imperative for stakeholders to guarantee that these systems are designed to uphold user privacy through the integration of functionalities such as user-managed privacy settings and robust data handling methods [83].

Furthermore, everything related to fairness and non-discrimination holds significant importance. Buolamwini and Gebru [69] have discovered that certain computer vision systems exhibit biases that result in inequitable outcomes, influenced by factors such as race and gender [84]. Hence, it is imperative for developers to adhere to ethical standards by mitigating biases in their algorithms and fostering openness in the decision-making mechanisms of their models.

Moreover, with the growing influence of computer vision on user experiences in the metaverse, there is a great significance of the concerns around digital wealth and engagement [85]. It is imperative to make concerted efforts in order to ensure that these technologies effectively enable positive experiences and cater to a diverse user base.

Based on all the above, the responsibility of addressing ethical considerations and upholding responsible practices in the development of computer vision technology in the metaverse lies with all stakeholders involved, including developers, platform operators, and users.

7. Conclusion

Computer vision has undergone significant development since its inception, including essential technologies and methodologies. This progress has led to its integration as a crucial component of the metaverse, facilitating the creation of lifelike avatars, interactive surroundings, and dynamic content. Case studies provide more evidence of the concrete effects of computer vision in this domain while also uncovering the difficulties and remedies linked to its adoption.

This work aims to deliver a comprehensive survey of computer vision techniques in the metaverse, focusing on their distinctive characteristics and identifying the key issues they are now facing. The conducted research revealed that computer vision is extensively used in metaverse-related applications for image recognition, segmentation, detection, and monitoring tasks. The latter tasks contribute to delivering VR/AR platforms and metaverse experiences empowered by AI capabilities. Examination of case studies where computer vision is integrated in the metaverse reveals its potential in multiple fields such as industry, fashion, healthcare, education, and more.

Research findings on related challenges indicate data privacy, the presence of biases, large computational demands, interoperability and adaptability issues, limited realism, and the need for enhanced accessibility of computer vision-based metaverse applications. Moreover, the environmental impact of the metaverse is highlighted, posing a serious influence factor for its adaptation. Limitations in hardware and software capabilities are also reported. In anticipation of future developments, the integration of computer vision with advanced machine learning methodologies and other sensory data, alongside the increasing prevalence of augmented reality and user-centric design, holds significant potential. However, it is imperative to exercise utmost attention to upholding moral obligations about privacy, fairness, and digital prosperity while actively pursuing these prospects.

To this end, this work indicates that computer vision emerges as a potent instrument in molding the metaverse, offering opportunities for innovation while necessitating the ethical deployment of this technology. The trajectory ahead entails a series of commitments and obstacles, fostering the anticipation of the enthralling prospects that await us.

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