Challenges for XR in Games

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Abstract. Extended Reality as a consolidated game platform was always a dream for both final consumers and game producers. If for one side this technology had enchanted and called the attention due its possibilities, for other side many challenges and difficulties had delayed its proliferation and massification. This paper intends to rise and discuss aspects and considerations related to these challenges and solutions. We try to bring some of the most relevant research topics and try to guess how XR games should look in the near future. We divide the challenges into 7 topics, based on extensive literature reviews: Cybersickness, User Experience, Displays, Rendering, Movements, Body Tracking and External World Information. We believe that this topics are a Grand Challenge, since the next generation of entertainment depends on adequately solving them in the near future.

Keywords: Extended reality · Virtual reality · Digital entertainment · Head-mounted displays · UX

1 Introduction

Extended Reality (XR) platform can be considered as an increment of Virtual Reality in relation to immersion and interaction aspects. While VR platforms are mostly dedicated to visual issues and AR uses real scenes as the main stage, XR includes more external elements and senses, such as movements, tactile, haptics and the usage of the real environment as the application stage [116]. According to the Milgram Continuum, the virtual immersion is a result that comes not only from accurate visual aspects, but mostly from a precise combination of all human senses, orchestrated in such a way that all of them enhances each other. While many progresses had been achieved in graphics, audio, tracking and interfaces issues, there are still many remaining challenges, mostly related to a correct combination on adaption to recent XR hardware devices. In this paper we propose a division of areas for these challenges. We believe that for a real consolidation for games within this platform it is necessary to have robust

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solutions in each field. We divide the challenges into 7 topics: cybersickness (CS), user experience and design guidelines, display and fovea, image quality and rendering, movements and redirect walking, body tracking and finally external world information and acquisition.

2 Cybersickness

Motion sickness (MS) is defined as the discomfort felt during a forced visual movement (without the same body movement), which typically happens in airplane trips, boats, or land vehicles. Such discomfort is also experienced in virtual environments and is called VIMS (Visually Induced Motion Sickness). MS can be split into two subcategories [53]: transportation sickness, which is tied to the real world and simulator sickness, which is associated to the virtual world and includes CS, as shown in Fig. 1. XR environments that use head-mounted displays (HMDs) are strongly related to common indications of discomfort [59]. Among the potential causes, CS deserves special attention as it is the most common and is usually associated to long exposures to HMDs. Additionally, more than 60% of HMDs usability problems are considerably related to discomfort [59]. The most persistent symptoms caused by CS are general discomfort, headache, stomach awareness, nausea, vomiting, sweating, fatigue, drowsiness, disorientation, and apathy [30].

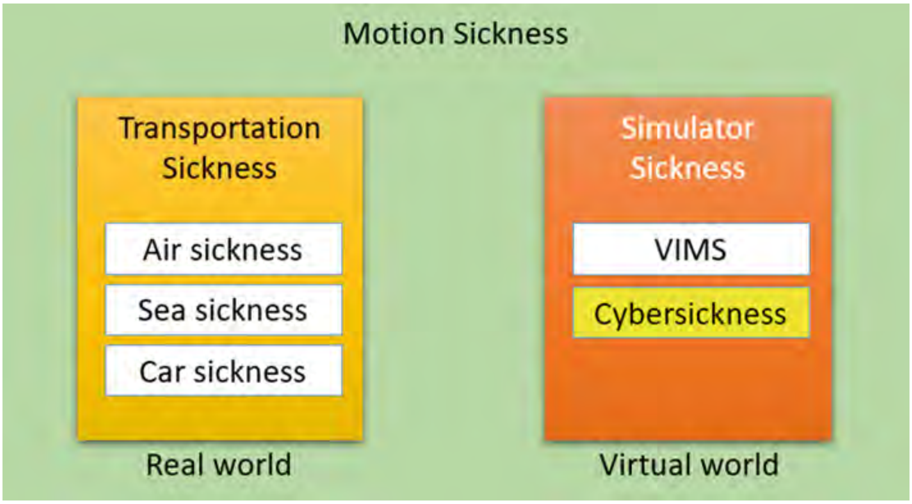

Fig. 1. Motion sickness and its subcategories according to environments and trigger mechanisms.

These symptoms influence the user experience and impact the profit and coverage of XR game manufacturing. In addition, discomfort symptoms can vary over people and tasks, where some individuals are more susceptible than others.

Several studies have been conducted using deep learning models to predict and mitigate CS, such as convolutional neural network (CNNs) and recurrent neural networks (RNNs) [47,57]. Although deep learning classifiers are the most suitable approach for CS prediction, deep neural networks are black boxes that are very difficult to grasp. In contrast, a recent approach apply techniques to make deep learning models explainable [121], although the literature is still scarce in the topic.

Furthermore, symbolic machine learning algorithms enable a straight understanding of decision paths [93]. Another critical problem in CS researching is associated with data labeling. In general, researchers collect verbal, haptic, or brain signal feedback to construct the ground truth of sickness. While verbal feedback is highly subjective and different from each participant, collecting haptic feedback when participants are under discomfort can often be corrupted by the delay associated with participant feedback. A straightforward challenge is related to gender differences tied to XR tasks.

Some works [28,37] pointed out that specific tasks can produce different results of CS for different user-profiles and groups. Additionally, Porcino et al. [92] suggested the importance of a better understanding of the correlation between profile attributes (such as gender, age, XR experience, and other individual characteristics) and gameplay elements, and also how outcomes obtained from profile attributes can be used to tag XR experiences according to distinct groups of users.

In this context, studies involving machine learning models combined with an evaluation of individual tasks associated with CS causes in XR games may produce a more profound study isolating any other XR possible influences on CS results. Overcoming these issues will help designers to produce better XR content and improves the user experience and retain users for longer XR exposures.

2.1 Review of CS Causes

Several factors can cause pain and discomfort when using HMD [126]. Manifestations of CS can lead to more intense symptoms, such as nausea, eye fatigue, neuralgia, and dizziness [54]. According to the literature [31,59,69,109], it is possible to highlight the main factors that contribute to the manifestation of CS symptoms.

1. **Locomotion** - According to Rebenitsch [99], locomotion can be correlated to CS. When the participant travels and has greater control of his movements and is close to natural movements, he will experience less CS. However, when the user experiences continuous visual movement stimulation while resting (also known as vection), it can induce painful sensations. Moreover, this problem reduces the time limit of using virtual reality in a comfortable state.

2. **Acceleration** - Visual accelerations without generating any response in the corresponding vestibular organs cause uncomfortable sensations that result in CS symptoms. High accelerations during movements produce higher degrees of CS [66,110]. An example of this report is considered by Laviola [66] using a virtual reality driving simulator as example. High-frequency acceleration movements contribute more to the CS. In contrast, the lower ones generate more comfortable experiences. This fact occurs because, during the acceleration increase, sensory conflicts can occur. Such conflicts make the body manifest discomfort information. However, the critical issue is the constant deceleration and acceleration. In other words, the duration of the acceleration change, not its magnitude, which makes people feel CS symptoms. An instantaneous acceleration from 0 to 100, instantaneous displacement, does not cause much discomfort than accelerations that frequently occur [1].
3. **Field of view** - In VR environments, a wide field of view generates a great sense of immersion. However, a wide field of view contributes to the CS manifestation. In contrast, a narrow field of view creates a more comfortable experience in VR but decrease the user's immersion [31,126].
4. **Depth of field** - Inadequate simulation of focus on stereoscopic HMDs with flow tracking devices creates unbelievable images and, consequently, causes discomfort. In the human eye, focus forces blur effects naturally that depend on the depth of field (DoF) and distance range of objects in the observed area. Due to ocular convergence, objects outside this range, located behind or in front of the eyes, are blurred [94].
5. **Degree of control** - According to Stanney and Keneddy [110], interactions and movements that are not being controlled by the user may cause CS.
6. **Duration use time** - Many works have showed that time exposure to VR experiences might raise discomfort in a proportional way [74,91,110].
7. **Latency-lag**, has persisted for years as an obstacle in the previous generations of HMDs [82]. Latency is the delay between action and reaction latency is the time difference between the time of input given and the corresponding action to take place in a virtual scenario. High latency may drastically increase CS levels.
8. **Static rest frame** - The lack of a static frame of reference (static rest frame) can cause sensory conflicts and, ultimately, CS [21]. According to Cao et al. [21] most users are able to better tolerate virtual environments created by projectors such as cave automatic virtual environments (CAVEs) [27] compared to HMDs devices.
9. **Camera rotation** - Rotations in virtual environments with HMDs increase the chances of sensory conflicts. The feeling of vection is greater in rotations when two axes are used in comparison to just one axis [13].

2.2 Review of CS Measurements

CS measuring is not trivial. The first problem is that the lack of a unique variable for discomfort level. VR users may experience multiple symptoms and some adverse effects that may not be described in the literature. Another difficulty is the considerable variation of CS susceptibility. Some users are more susceptible to CS symptoms than others. Meanwhile, research shows several ways to capture data for CS quantification. Such data can be classified as subjective, bio-signal and profile data (biological or behavioral profile).

1. **Subjective Data** - The best-known way to measure CS in VR is through subjective data captured from users by applying questionnaires. Such a methodology is simple and has been historically used. However, the results can be very subjective and dependent directly on the participants' responses.
   The Kennedy Questionnaire (Simulator Sickness Questionnaire - SSQ) [54] is the most cited tool for measuring manifestations reflecting most VR disease problems. In the SSQ, 16 symptoms of discomfort were grouped into three categories: oculomotor, disorientation, and nausea. The oculomotor assembly includes eye fatigue, trouble concentrating, blurred vision, and headache. The disorientation group comprises dizziness and vertigo. The nausea set covers upset stomach, increased salivation, and vomiting urges. When taking the questionnaire, participants classified each of the 16 symptoms on the following scale of discomfort: none (none), mild (mild), moderate (moderate), or severe (severe). The results of the SSQ are calculated and presented on four score scales: total disease (overall) and three sub-punctuations, i.e., oculomotor, disorientation, and nausea. To date, SSQ is the most widely used tool to detect symptoms of CS-associated discomfort [18,22].
   Moreover, each individual has a different CS susceptibility level. The Motion Sickness Susceptibility Questionnaire (MSSQ) [36,97] was not created for VR but it is sometimes used in VR studies [98]. The MSSQ can be used to determine the time taken by VR users to manifest MS symptoms in VR. This survey contains questions about the frequency with which individuals experience feelings of discomfort similar to those of MS. In MSSQ, the following scale is used: never, rarely, occasionally, and frequently. The issues are grouped into two phases of an individual's life: childhood and last "decade." This census made it possible to account for significant individual differences in MS levels.
   Kim H. et al. [56] revised and modified the traditional SSQ, proposing the Virtual Reality Sickness Questionnaire (VRSQ). The New VRSQ has nine items split in two classes of symptoms called "oculomotor" and "disorientation." Some recent research [123] has adhered to VRSQ use. Sevinc et al. [106] state that SSQ is not suitable for VR applications, given the psychometric quality issues. It also states as a disadvantage the fact that tests were conducted on 32 individuals only, which is an insufficient sample of all VR users.
2. **Bio-signal Data** - Electrical activity of the brain is bio-signal data that often helps detect illness and behavioral body symptoms. Electroencephalography (EEG) is a monitoring methodology used to record the human brain's electrical activity. Many diseases and brain problems are diagnosed through the evaluation of such devices' data. In adults and healthy people, signs vary depending on different states, for example, awake, aware, or asleep. The characteristics of brain waves also vary according to an individual's age. Brain

waves can be distinguished and separated into five different groups of frequency bands. These waves range from low to high frequencies. These are known as alpha, theta, beta, delta, and gamma waves [9,105].

According to studies [24,77], it is possible to capture (delta, theta, and alpha) from certain regions of the human brain. Such regions exhibit an Motion Sickness (MS) level. Lin et al. [68] found that 9–10 Hz values in the brain's parietal and motor regions are linked to MS levels. These values increased to 18–20 Hz in individuals exposed to MS. Other studies reported an increase in theta signal in situations similar to MS [46,79].

An individual's exposure to VR environments can induce stomach reactions. Studies used electrogastrogram (EGG) information to evaluate MS. According to Hu et al. [45] and Xu et al. [122], gastric myoelectric activities are MS indicators. Wink movements are linked to MS emergence [29]. Blinking and eye movement were observed in the work of Kim et al. [58]. Eye-tracking systems can collect information in VR environments (eye movement, pupil diameter, winks quantity, etc.) [89]. Unnatural eye movements can contribute to CS emergence. Eye fixation can minimize the effect of discomfort [125].

Through the body's electrodermic activity, also known as galvanic skin response (GSR), it is possible to obtain information about actions within the autonomic parasympathetic nervous system, which indicate alterations associated with cognition, emotion, and attention levels. [88]. Nalivaiko et al. [78] experimented with rats that were exposed to MS triggering situations. According to the authors, thermoregulation (sweating) disturbance plays a role in the pathophysiology of nausea. Despite testing on rats, similarities with human symptoms are verifiable. The work of Nalivaiko et al. concludes that nausea is part of the body's natural defense against poisoning and so validating the poison theory presented earlier in this review. Body cooling after "toxin" detection possibly represents a beneficial evolutionary "defensive hypothermia." This type of defensive hypothermia occurs in both humans and animals. Therefore, it is possible to conclude that visual or vestibular disorders can trigger the same type of defensive action by the human body. Studies have pointed out that the cardiac rate can significantly increase during experiments that cause MS [58]. According to Sugita et al. [111], cardiac frequency can be considered a strong indicator of MS or CS. In VR environments, Yang et al. [124] report that heart disease rates are even higher compared with other environments. Such cardiac elevation can induce visual discomfort [26].

3. **Profile Data** - VR user profile data such as gender, age, health condition, experience, and visual fatigue are associated with manifestations of discomfort.

   With respect to gender, women and men see in different ways [3]. According to Biocca et al. [10], women are more inclined to MS manifestations than men. According to Kolasinski et al. [59], this is due to a gender difference in the peripheral view. Women usually have wider FoVs than men. A wide FoV increases the likelihood of discomfort. Age is another factor that can increase CS or MS sensitivity.

According to Reason [96], susceptibility is a product of an individual's experience as a whole and relates to MS. This theory states that older people have less susceptibility to MS than children, for example. However, several studies [17,32,86] showed that older participants were more susceptible to MS than younger ones. According to Arns et al. [7], assuming that CS follows the same pattern as MS may lead to erroneous conclusions.

Previous studies show, for example, that MS is more prevalent in younger groups. However, the study by Arns et al. demonstrated that the opposite happens in the case of CS. This difference may also be because although MS shares some similarities with CS, it does not occur in virtually simulated environments. The theory of Reason et al. [97] treats experience as a whole, that is, life experience (from an individual's birth to one's present). The younger the individual, the less chance one would have to be exposed to such a situation. At the time of those publications, 1975 and 1978, driving and navigating would be experiences children would not normally experience. Nowadays, however, children can be exposed to CS symptoms through VR environments.

Moreover, health conditions can contribute to increased susceptibility to MS or CS once individuals are exposed to favorable environments. According to Frank et al. [35] and Laviola et al. [66], any symptoms, such as stomach pain, flu, stress, hangover, headache, visual fatigue, lack of sleep, or respiratory illnesses, can lead to increased susceptibility to visual discomfort.

Furthermore, flicker is a phenomenon of visual physical discomfort. Such a phenomenon causes physical and psychic fatigue [104]. Flicker sensitivity varies from person to person. An environment with high fps rates will possibly contribute to the user not noticing the flicker [10].

Eye dominance is an important information and has been described as the inherent tendency of the human visual system to prefer scene perception from one eye over the other [90]. According to Meng et al. [76], the eye dominance information can be used as a guide to produce less complex VR scenes without user perception loss based on foveated rendering. An efficient render produces high fps rates. Consequently, a high fps average contributes to avoid virtual reality discomfort.

Previous exposure to MS experiences are key in terms of discomfort susceptibility [63,96]. Individuals that are more frequently exposed to MS activities (e.g., driving, playing electronics games, etc.) are less susceptible to discomfort. This is most probably due to their ability to predict scenarios and situations in these environments [39].

3 Designing the Player Experience for XR Interactions

Since XR (including VR, AR and MR technologies) is a new technology and there are many people experiencing it for the first time, it is important that XR designers make their experiences as intuitive and memorable as possible. The gaming UX accounts for the whole experience players have with a game, from first hearing about it to navigating menus and progressing in the game. The question is: How to make a better game user experience (UX)?

It is not a novelty that the first issue prohibiting good evaluation of entertainment technologies is the inability to define what makes a system successful [101]. Differently from traditional user interfaces where the user is interacting to accomplish real tasks (for instance shopping, e-mailing, text editing and so on) in general during the game interaction the player is usually performing unreal tasks assuming be characters with some kind of special super power immersed in some fantasy world. On the other hand, similarly to traditional user interfaces, the player still needs to know how to interact efficiently and properly in order to be engaged as fast as possible with the game experience.

Celia Hodent [44] says UX is about understanding the gamer's brain: understanding human capabilities and limitations to anticipate how a game will be perceived, the emotions it will elicit, how players will interact with it, and how engaging the experience will be. In that way, looking to provide memorable and effective XR experiences, designers should be aware of how to deal with the following challenges while considering immersives interactions: confort [33] and cybersickness issues (see Sect. 2), design of appropriate scaling (size of virtual controls, buttons and font size), constraints, feedbacks, modalities of interactions (poses, gestures, gazing, voicing, typing [34]), guidance and instructions, locomotion and spatial affordance [107]. Besides that, ethical design principles in games, including gender representation, ethinicities, cultural aspects as well ethics of multiplayer games from an industry perspective [2] are timely and warranted.

Additionally, techniques commonly applied in the game user research with the goal to better understand the UX and provide very concrete and easy-to-use guidelines to anticipate and even solve UX design problems are those based on the user centered design approach as well on the cognitive and behavioral psychology. Examples of using such mixed methods are user interviews, surveys embedded into the own XR experience [84], usability heuristics for VR [50], usability testing, analysis of physiological signals [40], wizardOz [83], game analytics and quantitative behavioral telemetry. Finally, as other UX researchers [16], we believe by combining qualitative observation of issues, quantitative measures of player's emotions and analytics capturing player behavior in game can help tackle the game designer's intent, distinguish between intended and accidental difficulty, and identify only unintended challenges.

4 Displays and Foveated Rendering

The advent of wider Field of View HMDs with higher resolutions have increased shading complexities in rendering [5]. These advances brought a bottleneck of computing power, requiring some sort of optimizations for keeping the target frame rates, as conventional VR rendering is cost-full since two images have to be rendered. Trying to leverage the workload on rendering, some studies have suggested to create non regular pixel distribution (Foveated Rendering), knowing that the human eye has a non regular distribution of cones and rods.

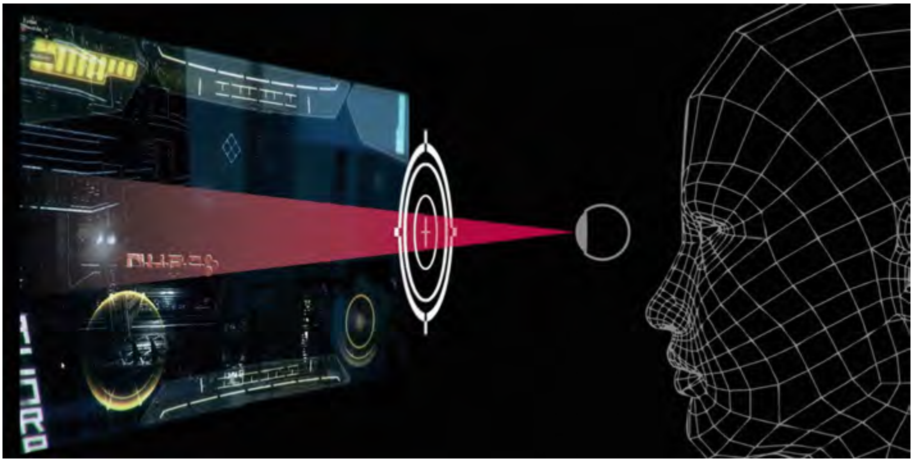

Fig. 2. Foveated rendering simulation. Source: [119]

Foveated Rendering refers to a technique that exploits the way the human eye works to render exclusively what is essential in a three-dimensional scene. According to Swafford et al. [114], usually the entire screen is rendered at the same resolution, regardless of where the user is looking. Since the human eye only perceives details in the center of vision, this uniformity in resolution, anyway of the user's focus, is a waste of valuable resources such as computing power. This technique uses an eye-tracker to determine where the user's gaze is and then, renders the peripheral parts of the vision at a lower quality, keeping the maximal quality possible only in the center of gaze. An illustration of this is found in Fig. 2. As human eyes have an inability to detect details outside its central field of view, the image generated by this optimization would still look the same even if it is rendered differently.

The first implementation of a computer generated image dependent of user gaze was made in 1973 by Reder [100]. He studied human attention by means of on-line monitoring of eye-position signals. Rendering aspects were not explored in the study. Only in 1989, Foveated Rendering was introduced by Levoy et al. [67] and applied to speed up rendering. They used the technique to ray tracing in 1989 to see how it could speed up the visualization of volumetric data. Their work had constraints on pursue lossless image quality feature because of high hardware latency used at that time, which made the transition of better-to-lower quality (or lower-to-better) on saccades visible to users.

Just in 2012, Foveated Rendering showed a more promising result for a general tridimensional scenario with the paper of Guenter et al. [38]. They designed a foveated renderer based on three layers of image quality and an anti-aliasing solution to minimize artifacts in lower resolution layers. The layer's radius, or foveated areas, around the gaze point were defined using a simple linear psychophysical model based on Minimal Angle of Resolution (MAR, the reciprocal of visual acuity), which is the commonly used linear mathematical model to compute visual acuity. They showed a performance improvement of 5–6x on desktop displays.

Since 2012, the field gained more strength in real-time rendering. Patney et al. [87] developed a rasterization Foveated Renderer with a smaller Fovea radius than Guenter et al., different pixel granularities and a modified temporal anti-aliasing based on TAA [60] that considers eye saccades as a variable of the algorithm's weights. Their two-layer foveated rendering design solved Guenter's problem of tunneling vision with the use of a contrast preserving peripheral blur. Weier et al. [120] and Koskela et al. [61] applied Foveated Rendering to real-time ray-tracing and path-tracing respectively. Instead of Guenter et al's work, VR displays were used in Patney et al. [87], Weier et al. [120] and koskela et al. [61], showing that foveated rendering could be used in VR scenarios.

While Foveated Rendering is already being implemented by some rendering engines, there are still many challenges for optimizing and customizing it. Besides finding a correct balance for the foveated areas, challenges such as understanding how this impacts human perception, color distortions and dynamic factors according with the game scene (games with constant colors in large areas naturally requires less pixels to be rendered and enhances the foveated optimizations). It is also important to create robust factors for measuring and better calibrating rendering parameters. Finally, we believe that this concept can also be transposed for different refresh rates for each foveated area, taking into consideration that rods are more dense at the peripheral human vision area.

5 Image Quality and Rendering

Increasing image quality and rendering in Virtual Reality is a demanding challenge, mainly for computational performance, and it requires sophisticated methods for rendering and simulating reality.

Path-tracing was first introduced by Kajiya via the rendering equation [51], as an integral equation that approximates optical reflection, and its numerical solution via Monte Carlo integration methods. It is currently the state-of-the-art in interactive and real-time rendering, since it is able to achieve a higher degree of realism needed for demanding graphical applications such as movies and games. It can faithfully simulate graphical effects such as soft shadows, indirect lighting, reflectance and others. This is mostly due to the nature of the method, which makes the light bounces to a random direction when it reaches an object, calculating the color contribution until it reaches the camera - or the backwards path, depending on the implemented method.

It does so for every pixel in a scene at least once (1 sample per pixel), making the performance directly proportional to the number of pixels of the target

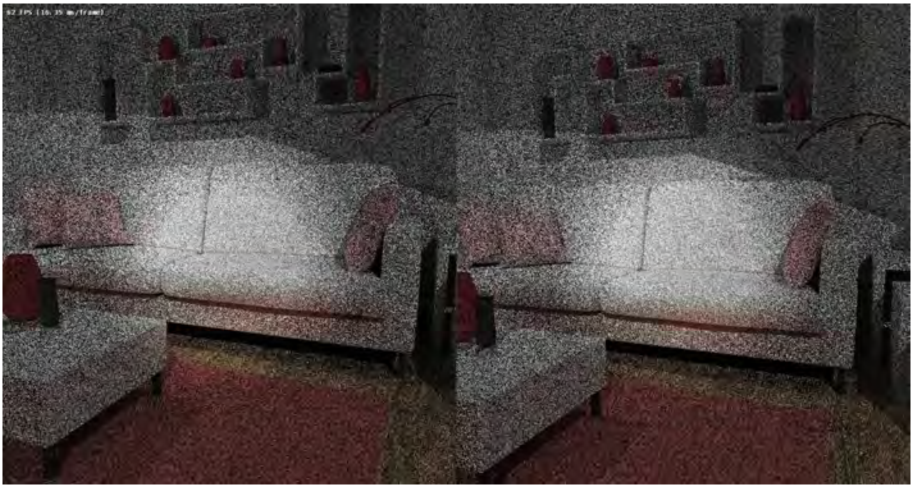

Fig. 3. Path traced image in dual screens using foveation, before denoiser.

resolution. In HMDs, the resolution can range from 1,440 × 1,600 up to 2,880 × 2,720 per eye. Furthering the challenge, add to this the need to render it at least 90 times per second.

Hardware optimizations were made both in CPU and GPU, Nvidia recently released the RTX architecture [55], access to GPUs capable of optimizing the intersection calculation of a ray with a polygon, having BVH optimization features and, thus, accelerating realistic rendering became available for the mass market.

Approaches such as hybrid rendering combines both rasterization and path-tracing in different stages of the rendering pipeline [8], and have the advantage of reducing the amount of samples per pixel and per frame while achieving high-quality results for real-time rendering.

For HMDs with eye-tracking technology, we can further reduce the total number of samples per pixel using foveated rendering techniques. By using the properties of vision such as the concentration of cone distribution in the fovea and devices that allow tracking of the user's gaze, we can avoid rendering parts of the screen with such sharp details or rendering at a reduced spatial sampling frequency. Previous studies have experimented based on user studies to define what an optimal distribution would be, with probabilistic selection of which pixels will be selected by rays, thus decreasing the amount of traced rays and optimizing the algorithm [120]. Similarly, other studies use a fixed texture for ray selection.

Path-traced images requires a high number of samples per pixel to achieve a high fidelity rendered frame. By using fewer samples, the image is left with a high variance also known as noise. Reconstruction algorithms known as denoisers are already commonly used in path-tracing rendering, lowering the variance left in the lighting step with fewer samples per pixel, and thus increasing the performance of the rendering pipeline. Current algorithms for denoising apply different techniques, such as frequency analysis, nonlinear filters, sampling techniques, and deep learning, to name the most important [129].

Using denoisers in combination with foveated rendering techniques is further required since such an optimization haves even fewer samples than the conventional path-tracing, as shown in Fig. 3.

Reconstruction algorithms known as denoisers, which are already commonly used in path tracing rendering, are even more relevant with the fovea distributions, as shown in Fig. 3. It can achieve a lower variance with few samples per pixels, increasing the performance of the rendering pipeline.

In VR, it is possible to use log-polar space rendering and adapt reconstruction to be compatible to it in the early stages of rendering [61], making it possible to obtain a distribution close to the cone distribution of the fovea, with a higher concentration in the center.

6 Real and Virtual Movements

Moving is another form of people unconsciously and continuously interacting with their surroundings daily. Locomotion techniques are one way to change the user's state from a passive to an active character in the environment, creating a deep sense of existence and enhancing the experience [64]. However, there are challenges for each type of locomotion [25,64]. Albert summed them up into three fundamental challenges: sickness, presence, and fatigue [4]. This section will present the types of locomotion and the problems attached to movement in XR.

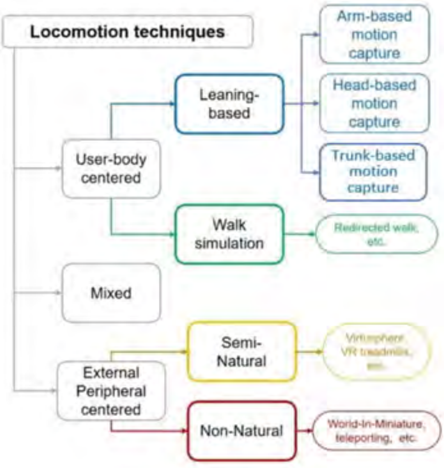

Fig. 4. Virtual reality locomotion techniques taxonomy. Source: [25]

Several researchers proposed classifications for all locomotion techniques [4,6,12,15,25,112]. Cherni proposes a taxonomy of locomotion techniques in virtual reality based on whether the input is body-centered, external peripheral centered, or both [25]. Figure 4 shows visually how the techniques are separated. The three main groups' names are User-body centered, Mixed, and External Peripheral centered. User-body centered are techniques based on the user's movement such as leaning the head [43,128], swinging arms [19,75], or even natural walking as inputs [49,62,73]. External Peripheral-centered techniques are hardware-based inputs such as omnidirectional mills [19,118], teleportation (Fig. 5), and the use of a joystick [43,65,102]. The mixed types are techniques that apply both categories simultaneously, such as holding a controller button while swinging an arm or using the joystick to move in the virtual space while the rotation is done by rotating the head [43,102].

Fig. 5. Teleport locomotion technique. Source: [25]

Even though there are several solutions for creating a way to move in a VR environment, there is not yet one better solution for every application [4,12,25]. Each method has its pros and cons, but there are typical problems in all techniques, as mentioned before. The first one, and already seen in this work, is sickness, caused by dissonance between the motion visualized in the virtual environment and the motion felt in the real world [4]. A problem common in the External Peripheral centered class since the ones which reduce motion sickness are the body-centered self-motion techniques [25].

The next challenge is presence, better described as the sense of presence. Slater defines it as the user's sense of being in a virtual world, which enhances immersion, that is, the technical description of the virtual environment capable of producing the sense of presence [4,108]. Techniques based on natural walking are considered the most presence-enhancing form of locomotion [12,64,80,95,112]. However, unlike the other challenges, any technique can break the immersion since its use may create a more profound or shallower interaction depending on the design of the experience [15,25].

The last main challenge is fatigue. This ergonomic issue is less known than the others since it appears after continued use of the HMD. Although, while developing an application evaluating this problem can be determined its success. It is worst in walk base techniques and treadmills. In other words, techniques where the user needs to move [4,81].

There are specific challenges for specific solutions, besides the three main problems mentioned by Albert [4], that are worth mentioning. Most external peripheral-centered semi-natural techniques are expensive and challenging to use and maintain, therefore not considered a viable option to implement [19,25]. However, researchers are working on them because it can be an option in the future to solve the main three problems [11,41]. Another locomotion technique recognized as promising to solve three main problems is Redirect Walking [20].

This solution aims to create, in the user, the feeling of mimicking his movement by misleading his senses [49]. Redirect walking tricks the user's perception and makes him feel that he is walking forward, but he is walking on a curved path. The main problem with this is how to shift the virtual environment without triggering the user's perception, which can cause cybersickness and break the immersion. Instead of only diverting the player's movement or turning the whole scenery, researchers use devices, tools, and methods to improve Redirect Walking. Methods such as pointed out by Sun [113] recognize when there is saccade movement of the eye and shifts the scene simultaneously. Redirect walking is the least used method of movement in VR applications mainly because of the necessity of bigger spaces to fully reach its potential of making the user unaware of the reorientation of his movement. Matsumoto [73] experimented that a circular arc of 22 m is necessary to avoid perception, but Rietzler [103] managed to constrain the movements to an area of 6 m × 6 m. Even though there are advances in this topic, it is still necessary to develop more efficient methods for inferring the smaller required spaces for each situation (Fig. 6).

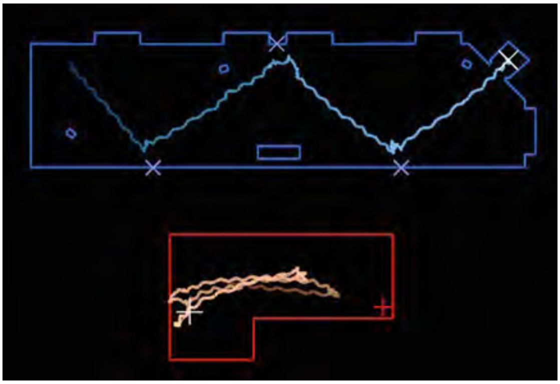

Fig. 6. Redirect walking. The blue region shows the virtual environment, and the blue wiggled line is the virtual path the users chose to move. The red area is the real-life area and the red line is the user's path made imperceptibly. Source: [49] (Color figure online)

As said by Qi and supported by other authors, locomotion is one of the most critical forms of interaction in VR [64,95,113]. Therefore, choosing which method to implement is crucial. It is a choice based on the use of the application and analyzing which problems are worst to the experience and should be solved. Cherni even adds a table to his work, showing the better techniques depending on which body parts the user will dedicate to the locomotion [25]. Hence the technique should be a design-driven choice.

7 Body Tracking

XR games must provide users with an immersive experience with a sense of presence and satisfying natural interaction. Body tracking allows reconstruction of the body movement needed to achieve a satisfying natural interaction [52], especially in multiplayer games [48], enabling users to observe other players' movements.

A virtual body is crucial for a good level of immersion, and when the user identifies himself with this virtual body, we can see the feeling of presence [108]. Although there are many important works related to the subject [23], most are related to showing only floating hands or VR controllers due to the lack of movement data.

In the application domain, XR in Games, vision-based body tracking remains a challenge because of sudden object motion changes, cluttered background, partial occlusion, and camera motion. The hands are the most used body parts in XR in games, as they provide a robust form of interaction. Consequently, vision-based hand-tracking is a topic of interest for several researchers. Most work on hands-tracking focuses on the use of depth cameras [115] or RGB [83]. Depth-based approaches present results that are superior to RGB-based approaches. A depth camera provides hand geometry in terms of a 2.5D point cloud, and the model-based approaches can reliably fit a hand mesh to the reconstructed point cloud [115].

Using hand tracking input with mobile technology is a problem mainly due to the high energy consumption. Han et al. [42] present a real-time tracking system that uses four egocentric monochrome fisheye cameras to produce 3D hand pose estimates and run not only on PC but also on mobile processors. On PC runs 60 Hz and 30 Hz on a mobile processor (Fig. 7).

The detection-by-tracking method of Han et al. [42] utilizes neural network architectures for detecting hands and leverages tracking history to produce spatially and temporally consistent poses. Besides, the system supports a large working volume for a diverse set of users and runs in various real-world environments.

The method mentioned presents failures under complicated hand-hand interactions (Fig. 8a), an uncommon view of the hand for egocentric cameras (Fig. 8b) and hand-object interactions (Fig. 8c and 8d), showing that grasping objects and training data generation are still open issues in mobile hand tracking interactions.

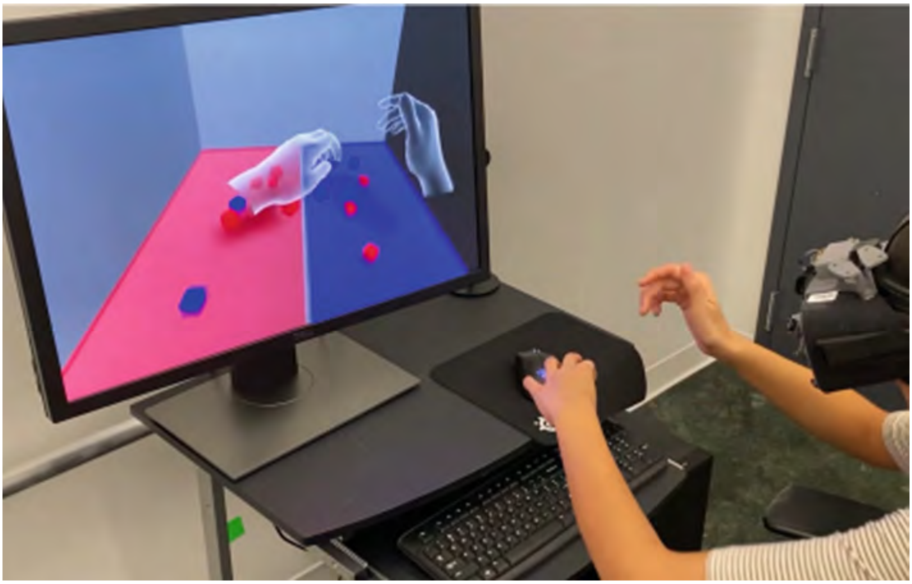

Fig. 7. A real-time hand-tracking system using four monochrome cameras mounted on a VR headset. Source: [42]

8 External World Information

Acquiring and processing the external world information is an essential and challenging aspect of XR applications. Real-world data acquisition for XR applications comes from different sources such as motion sensors, cameras, depth sensors, and other hardware. Aggregating and incorporating this data into meaningful information for XR games is not a trivial task.

Considering the visual features of XR applications, one crucial aspect is the consistent appearance between virtual and real-world objects. One of the main characteristics that drive the consistent appearance is the lighting between virtual and real-world objects. In this context, the external world information is the real-world lighting.

One possible approach to solving this problem is to relight a real object into a particular lighting setting around this object. This solution is usually applied to well-known objects, such as faces [85] and architectural entities [14]. This approach works by bringing the real-world domain to the virtual-world domain. It implies that the real world is adjusted to match the virtual world. It works well for inserting a few objects into the virtual scene, like an object viewer in augmented virtuality, where one real-world object is centered in the user's view. However, this is not a realistic scenario for general XR applications where a scene contains hundreds to thousands of objects from the real-world domain. Relighting the whole real-world environment in real-time is still an open challenge.

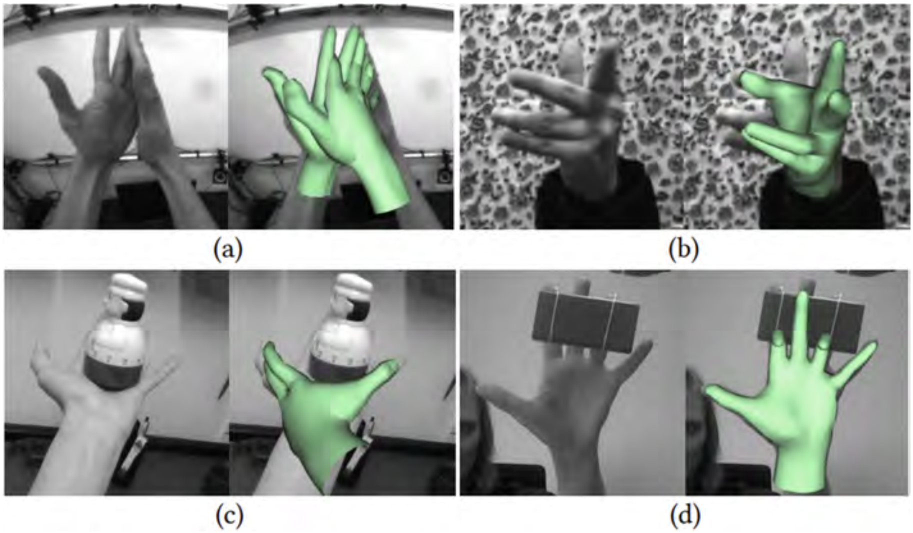

Fig. 8. The system usually fails under complicated hand-hand interactions (a), uncommon view of the hand for egocentric cameras (b) and hand-object interactions (c), (d). Source: [42]

Another way around is to bring the virtual-world domain to the real-world domain. This can be accomplished by getting the lighting information from the real-world scene and using this information to render the virtual objects. Usually, in XR applications, all the lighting information is estimated from pictures of the environment. A common source of information is the frames of real-time videos captured from cameras in the user's HMD.

An approach that uses this perspective to solve the problem can be easily extended to all the virtual objects, hence, relight all the virtual objects in the XR scene (Fig. 9).

Some works have been developed to estimate a global environment lighting of the real-world [70,71]. Using global environment lighting to relight virtual objects implies that all places in the scene receive the same global illumination. Thus the environment lighting is spatially invariant. This is a reasonable approach for straightforward scenarios with a limited field of view and without objects obstructing the view or casting shadows in the localized spots in the scene. For instance, a fixed camera pointing at an unobstructed surface would be a good example.

Recently, methods that consider spatial variance have been developed [127] [72]. These methods use special representations of the lighting and distinctively crafted datasets that allow a neural network to learn the spatial information from the data. The rendering of virtual objects using the estimation from those methods produces plausible and high-quality XR environments. The spatially varying feature of those methods enables each object to have particular lighting

Fig. 9. Left: rendering of XR scene with inconsistent lighting. Right: relighting of XR scene with consistent environment lighting.

based on the spatial localization of the object in the scene. Thus an object in a shadowed area would not receive the same lighting as the object in a bright spot at the scene.

Figure 10 depicts a global and a spatially varying environment rendering of an XR scene. In the global lighting setting, on top, all of the bunnies are rendered using the same lighting, thus sharing the same appearance independent of the placement in the scene. In the spatially varying rendering, the bunnies have different lighting settings for each position in the scene, producing a natural appearance for every instance of the virtual object in the scene.

The methods mentioned in this section share a common characteristic. All of them use deep learning techniques to estimate the lighting information. A characteristic of deep learning methods is the dependence of an enormous quantity of data to produce outstanding results. In the previously mentioned work of Marques et al. [71], the training data were created through the generation of synthetic samples using computer graphics due to scarcity of datasets portraiting environment and real-world measured lighting. There is a trend in using synthetic data for training neural networks where real-world data is unavailable.

The usage of real-world data mixed with synthetic data can significantly improve neural network estimations by providing a rich context for the neural network by combining the advantage of creating a high quantity of data while maintaining the features of the real-world samples. This element can be explored to allow improvements in the lighting estimation characteristics, such as color consistency [72].

(a) Global lighting

(b) Spatially-varying lighting

Fig. 10. Top: rendering of an XR scene using global lighting estimation. Bottom: rendering of an XR scene using a spatially varying lighting estimation. Source [72].

The challenge for lighting estimation still resides in creating a suitable method for real-time applications to estimate lighting in a time-consistent manner. Time consistency is an essential feature for XR applications since abrupt changes in lighting can potentially worsen the user's immersion. The state-of-art has solved the problem regarding the spatial variance of the lighting and color consistency [127] [72]. However, those methods use the information of one frame at a time to produce the results, hence having limitations with time consistency on real applications.

As the writing of this paper, there is no publicly available dataset from real-world measurement that can capture all the features necessary for creating knowledge for lighting estimation considering time, spatial, and color consistency. Furthermore, acquiring such a dataset is not a trivial task. Progress in training neural networks using natural and synthetic data seems a promising step to achieve a complete solution for XR lighting estimation. The usage of Generative Adversarial Network [117] to generate such a dataset has demonstrated excellence in other tasks and could be explored for external world data estimation and further improve the XR experience regarding visual fidelity.

Extracting and estimating external world information is still considered a difficult task. Developments regarding the representation of the information, including the recent advancements in computer vision methods, can dramatically improve XR environments by allowing new forms of interaction between the virtual and the real world.

9 Conclusion

Extended Reality as a game platform has an incredible potential, due its high immersive conditions. However, it is a totally new computational and ubiquitous environment and brings many challenges and problems, some of them not trivial. In this work we categorize these issues in 7 different topics, although there can be many others: cybersickness (CS), user experience and design guidelines, display and fovea, image quality and rendering, movements and redirect walking, body tracking and finally external world information and acquisition. This classification is not exhaustive and there are many other aspects that could also be included, such as audio, new interface devices and collaborative environments.

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