Optics and Photonics Technologies Serving Virtual Worlds

authored by a Joint Focus Group of

Photonics21

and

Members of the European Virtual and Augmented Reality Industrial Coalition

Peter Schelkens (chief editor), Julien Castet, Kayvan Mirza, Ilmars Osmanis, Uwe Vogel *et al.*

This document synthesises the outcome of a joint Photonics and Virtual Worlds workshop organised in November 2023, under the lead and direction of Directorate-General for Communications Networks, Content and Technology Units A3, Microelectronics and Photonics Industry and G2, Interactive Technologies, Digital for Culture and Education.

January 2024

Context

The recent Communication on the long-term competitiveness of the EU[1] "identified Web 4.0 as a ground-breaking technological transition towards a world where everything is seamlessly interconnected. The European Council has called for the European Union to stay at the forefront of Web 4.0 development. Virtual worlds are an important part of this transition to Web 4.0. They are already opening up a wide range of opportunities in many societal, industrial and public sectors. The concept of Virtual Worlds has been around for decades, but they have now become technically and economically feasible thanks to rapid technological advances and an improved connectivity infrastructure. Virtual worlds will be an important aspect of Europe's Digital Decade and will impact the way people live, work, create and share content, as well as the way businesses operate, innovate, produce, and interact with customers." The Communication from the Commission, named *An EU initiative on Web 4.0 and virtual worlds: a head start in the next technological transition*, sets out the strategy and proposed actions on virtual worlds and Web 4.0[2].

In this context, optics and photonics technologies are crucial for realizing sensing and visualization devices supporting Virtual Worlds applications. Moreover, they offer opportunities to improve the quality, performance, and efficiency of processing and communicating Virtual Worlds' content.

Worldwide, the market for optics in Virtual, Augmented, and Mixed Reality (VR/AR/MR, jointly known as XR- Extended Reality) expects growth from US$ 593 million in 2024 to US$ 5100 million in 2034. About 80% of the leading manufacturers of these devices are located in Asia and the US[3]. Hence, Europe must strengthen its position.

Ideas for future research and innovation priorities, cutting-edge technologies and co-designed solutions for a successful Virtual Worlds Adoption by 2030

Notwithstanding the significant efforts invested by major tech companies, start-ups, universities, research institutes, and governments, considerable challenges remain to be addressed to realize solutions that offer high-performance, excellent visual quality, high-quality user experience, and sustainable services and devices. Optics and photonics are the key enabling technologies to achieve this goal for head-mounted displays (HMD), autostereoscopic displays, and sensing devices.

Optics & Photonics for Display Devices – Currently, commercial head-mounted display solutions rely upon high-end microdisplays deploying various technologies such as organic light-emitting diodes (OLEDs), micro-LEDs, liquid crystal on silicon (LCoS), or microelectromechanical systems (MEMS). Nonetheless, these microdisplays will still need to undergo further improvements regarding power consumption (<1 mW), device efficiency, resolution (8K and beyond, pixel densities > 10kppi), high dynamic range (HDR), colour gamut, contrast and refresh rate. Besides utilizing classical visualization modes, plenoptic modes such as light field, multifocal and holography are gaining ground, holding the promise for truly immersive experiences and potentially improving vergence-accommodation behaviour for HMDs and autostereoscopic displays. Both the classical approach and the plenoptic solutions require not only a significant evolution regarding the capabilities and features of the opto-nanoelectronic display devices – such as light-field (micro)displays, multifocal light engines, spatial

[1] COM(2023) 168 final

[2] COM(2023) 442 final : [An EU initiative on virtual worlds: a head start in the next technological transition | Shaping Europe's digital future (europa.eu)]

[3] Source : IDTechEX, https://www.idtechex.com/en/research-report/optics-for-virtual-augmented-and-mixed-reality-2024-2034-technologies-players-and-markets/969

light modulators (SLMs) based on LCOS, and MEMS – but also state-of-the-art optical systems and architectures.

These complex optical systems must support the required field of view (FoV), be lightweight and safe for the user, and provide excellent colour uniformity and high brightness efficiency. Furthermore, they must satisfy the use case requirements for both professional use and mass adoption, i.e., be scalable to large volumes (cost-effective). The optical system will ultimately determine the image quality and, therefore, the end-user experience and market adoption of XR devices.

Within this optical system, the design and fabrication of waveguide optics, holographic elements, diffractive optics, reflective light guides, freeform optics, and meta-surfaces with optimal optical properties and behaviour are crucial. They will be deterministic in obtaining the required form factors and user experience for the envisioned display devices. Furthermore, photonic integrated circuits and light-shaping optics based on liquid crystal devices, enabling the miniaturization of, e.g., waveguides, couplers, and lasers, combined with more macroscale components such as lenses, will also be essential to reach these goals.

Optics & Photonics for Sensing Devices – Eye tracking and gaze estimation technologies are essential for extended reality experiences. However, they face challenges such as accuracy in diverse lighting conditions and with different eye physiologies. The precision in detecting subtle eye movements or distinguishing between intentional gaze and casual looking remains a limitation. Additionally, integrating these systems seamlessly into mixed-reality devices without increasing bulk or reducing comfort is challenging.

Depth-sensing technologies like structured light, time-of-flight, and stereo vision are pivotal in mixed reality for understanding the environment. Structured light systems, while accurate, can be hampered by ambient light interference and have a limited range. Time-of-flight sensors offer a better range but can struggle with object details and edge detection. Stereo vision, reliant on algorithmic processing of images from two cameras, faces challenges in texture-less or feature-poor areas. While providing detailed surface information, photometric stereo is not widely used in dynamic environments typical for mixed reality due to its reliance on multiple light sources.

Finally, in extended reality, capturing content using high-end cameras, LIDAR, light-field, and holographic technologies offers vast potential but comes with limitations. High-end cameras can provide high-quality imagery but are often bulky and expensive. LIDAR offers excellent depth information but typically lacks qualitative colour data and struggles with transparent or highly reflective surfaces. Light-field cameras enable the capturing of light intensity and direction but are computationally intensive and currently limited in resolution. While promising for creating three-dimensional images, holographic cameras are still in an early stage of development with limitations in resolution, field of view, and processing requirements.

Algorithmic Design and Software – Coupled with these sensing technologies, *algorithms* and metrics must be designed to exploit the underlying light (transportation) models given the utilized modality and address scene representation, modelling, content generation, compression, transmission, content reconstruction, content-to-display adaptation, and rendering. The algorithm's efficiency should reduce system delay (latency) as well. To increase interoperability, associated *software development kits (SDKs) and open-source algorithms* should be developed.

Embedding AI-based strategies will most likely be essential to achieve the desired algorithmic behaviour and performance, and might help reduce the system's complexity. *Edge AI* promises to be especially useful in this context and allows further reduction of latency, enhanced privacy, security and algorithmic scalability.

Co-design and Standardization – Several overarching challenges must be addressed for further advancement of XR applications. A critical need exists for high-performing yet *sustainable and cost-effective solutions*, particularly in XR display and sensing devices. Displays should offer high resolution, a large field of view, and excellent depth perception, ranging from head-mounted to large-scale displays. Developing such technologies involves (early) intricate *co-design between photonics and XR components (hardware, software, interface, process engines, AI), which poses significant production* challenges both from the perspective of integration and the design of individual components. Sustainability is a key concern, encompassing the materials used, power consumption, and recycling processes.

Another pressing issue is the lack of *standardization*, which hinders interoperability among novel XR devices, an essential factor for broad adoption. Standardization should address both technical/physical and application levels, e.g., how users can seamlessly switch between different virtual or augmented applications and worlds.

Quality and User Experience – Additionally, methodologies to assess *human perception and experience* from subjective, objective, and functional perspectives will need to be defined, accounting for the specific properties of these new device types. This also needs to involve psychological, social, and educational aspects of users in virtual or augmented worlds. Facilitating the uptake of this technology requires addressing various aspects such as inclusive design, diversity of users, and concerns related to *privacy, security, ethics, legalities, physical and psychological risks*, and creating environments conducive to producing rich content. The quality of integration, both from a user and technological perspective, will be essential for realizing a broad adoption.

Cross-fertilisation between XR and Photonics

Links between the two domains could be further explored and deepened. The two communities can help design the Virtual Worlds applications and devices of the future together and benefit from each other. The Photonics community welcomes ideas for concrete use cases, examples of hardware limitations and needs for better immersive systems. The XR community has an interest in anticipating technological challenges and progress when it comes, for instance, to displays or sensors and integrating faster results and new solutions.