A Historical and Current Review of Extended Reality Technologies and Applications

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Abstract

This paper provides a review of Extended Reality (ER) technologies and applications. The different technologies related to ER, such as Virtual Reality, Augmented Reality and Mixed Reality are introduced and explained, following an historical perspective. The basic technical concepts behind these technologies are briefly explained. Current applications are presented, including references to actual tools and systems, in order to clarify the concepts and the potential of the technologies.Â

A Historical and Current Review of Extended Reality Technologies and Applications

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***Index Terms*— Extended Reality, Augmented Reality, Virtual Reality, Mixed Reality**

I. INTRODUCTION

Technology is transforming the way we interact with the world. Extended Realities (XR) have emerged as a set of technologies that are taking the human experience to unprecedented levels of immersion and connection, both with the real or physical world, as well as with digital or virtual worlds. Within XR technologies, there are Virtual Reality, Augmented Reality and Mixed Reality, each with its own characteristics and applications. A conceptual outline of these realities is shown in Figure 1,

Virtual reality (VR) is a technology that creates a completely digital world within which users can explore and interact. The real world is outside this virtual world. For example, with VR glasses or headsets that completely cover the visual field of users, it is possible to immerse themselves in totally virtual worlds. Augmented reality (AR) is a technology that allows information and digital content to be superimposed on the real world. For example, some AR apps allow users to see information related to real objects, how a piece of furniture would fit into a room before buying it, or how a new car would look in a different color. Mixed Reality (MR) combines elements of VR and AR to create hybrid experiences, where virtual objects interact with the real environment in a realistic way. For example, a virtual object can hide behind a real object, or interact digitally with it.

In 1994, Paul Milgram defined these technologies in terms of a *continuum* relating purely virtual environments to purely real environments [1], and represented it as shown in Figure 2. The figure depicts a solid line linking a real environment (on the left) and a completely virtual environment (on the right). Along this line could be located the different technologies of XR.

This article describes the characteristics of each of these technologies, a historical overview and current uses for various types of use cases and industries.

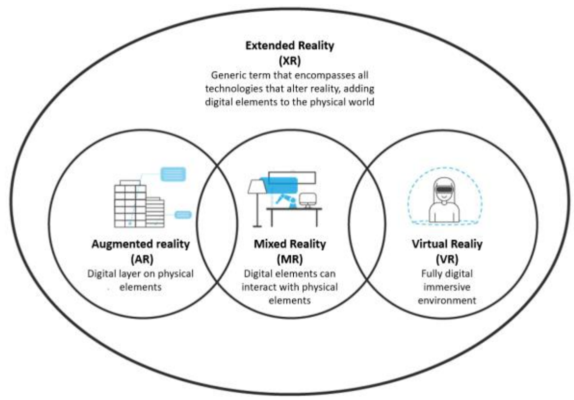

Figure 1. Concepts of AR, MR, VR and XR. Based on [2].

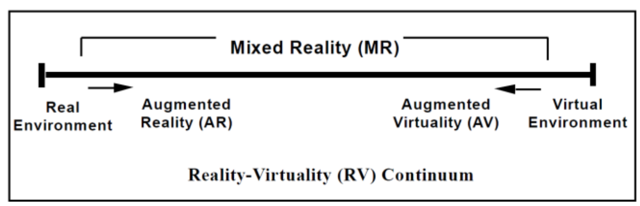

Figure 2 – Continuum relating purely real environments with purely virtual environments [1].

II. VIRTUAL REALITY

VR transports users to completely virtual, computer-generated worlds where they can explore and live experiences outside the real world. Through the use of devices such as headsets and specialized controllers, VR immerses users in three-dimensional multimedia environments that stimulate their senses of sight, hearing, and sometimes even touch and smell.

The first practical Virtual Reality device was *"Sensorama"*, patented in 1962 by Morton Heilig [3]. The conceptual scheme presented in the patent is shown in Figure 3. According to an article published in 1964, Sensorama *"attempts to engulf the viewer in the stimuli of reality. Viewing of the color stereo Sensorama film is replete with binaural sound, odors, winds, and vibrations. The original scene is recreated with remarkable fidelity. At this time the process comes closer to duplicating reality than any other system we have seen."* [4] The device,

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shown in Figure 4, provides a controlled environment, where the viewer's head is immersed in the equipment, with individual eyepieces for each eye, odor ducts, wind blowers, binaural speakers, and seat with vibrating armrests. The device can be seen in operation, with several details in [5].

In 1963, science fiction inventor and publisher Hugo Gernsback proposed the realization of a prototype of *"teleyeglasses"*, a battery-powered device that uses a pair of cathode ray tubes to display stereoscopic television programs [6]. In Life magazine of July 26, 1963 [7], Gernsback stated that *"It is now perfectly possible to make thin, inch-square cathode tubes and to run them with low-voltage current from very small batteries with no danger at all of electrocuting the wearer. Sound can be carried to the ear just as a hearing aid. Television eyeglasses should weigh only about five ounces (140 grams). Since there will be a picture for each eye, the glasses will make a stereoptical view possible… The user can take them out of his pocket anywhere, slip them on, flip a switch and turn to his favorite station".* Figure 5 shows Hugo Gernsback with his prototype "teleyeglasses". However, this was only an idea, which had no practical or commercial implementation at the time.

In the mid-1980s, NASA worked on designing VR devices, with the goal of exploring planetary environments [8]. Figure 6 shows the prototype VR headset, developed in 1985 by Jim Humphries and Mike McGreevy at NASA's Ames Research Center. The system created a computer-generated image of what a pilot might see during a real flight [9]. In 1986, the same authors published new results of the work they carried out, with a lighter helmet, as shown in Figure 7 [10]. In addition to the helmet, the user could interact through spoken commands using a voice recognition system. For tactile interaction with the three-dimensional environment, the user used lightweight glove-like devices, which transmitted data records of the shape and position of the arm, hand, and finger to a central computer. The gloves were equipped with flexion-sensitive devices at each finger joint, between the fingers and in the palm of the hand. Figure 7 shows an example of what the user saw using the entire system.

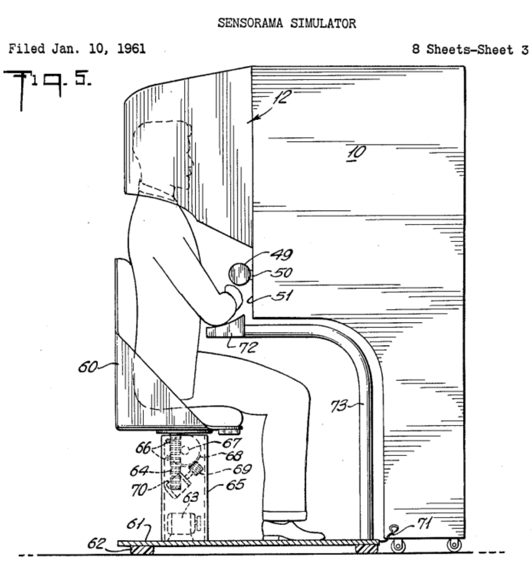

Figure 3 - Schematic of Sensorama, as shown in Morton Heilig Patent [3].

Figure 4 – The Sensorama machine in operation

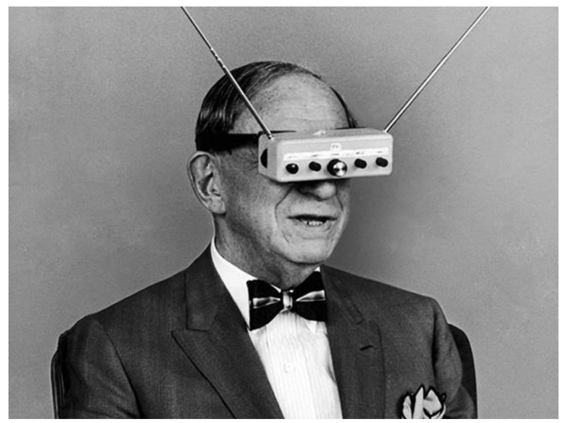

Figure 5 – Hugo Gernsback with his prototype of "teleyeglasses" in 1963 [7].

Figure 6 – VR headset prototype, developed in 1985 by Jim Humphries and Mike McGreevy at NASA's Ames Research Center. The system created a computer-generated image of what a pilot might see during a real flight.

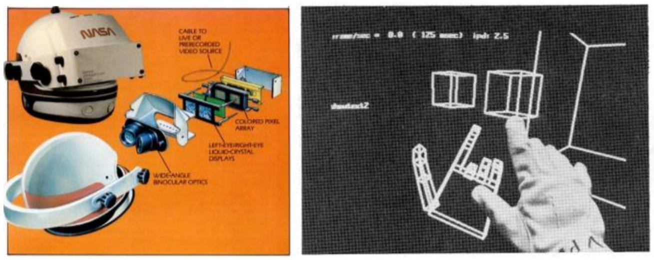

Figure 7 – Left: VR headset, developed by NASA [11]. Right: Virtual objects in 3D graphics and articulated hand, controlled directly by NASA's VR system [10]

Based on NASA's advances, several companies began developing VR technology for home uses. In 1987, Popular Mechanics magazine featured an article titled "3-D TV comes home", detailing different VR products for watching movies and games [11]. Among them, a Sega system stands out, as the first practical 3D gaming system marketed in the United States (see Figure 8).

Figure 8 – First 3D entertainment system in the US [10].

In 1994 the Nintendo company announced the launch of its new VR console for video games, called Virtual Boy [12]. Virtual Boy used a display technology developed by Reflection Technology Inc. To play, the user had to look directly at two miniature screens to see stereoscopic images created by arrays of red monochrome lights produced with LED technology. The equipment and visualization of some games can be seen in Figure 9. Despite the great development effort, of more than 4 years, the product was not successful. With around 770,000 units sold, it was Nintendo's worst-selling console of all time and was discontinued shortly after its release [13] [14].

Until 2010, there was no virtual reality headset in the video game market that was truly immersive. On that date, Palmer Luckey, an enthusiastic and self-taught 18-year-old, assembled a prototype of a virtual reality headset in the basement of his parents' house, which he called Oculus Rift. Luckey posted his progress on Internet forums in 2012, thinking about getting funding on the Kickstarter platform [15]. John Carmack, a pioneer in several video games such as Doom and Quake, found his publications and the two began an online dialogue [16]. Luckey sent Carmack a prototype, which Carmack demonstrated at the E3 video game conference in 2012 [17]. Sponsored by Carmack, Luckey attempted to collect $250,000 for the Oculus Rift on Kickstarter and collected $2.5 million! [18]. A year later, in 2013, it received $16 million in venture capital [19]. The first Oculus Rift equipment had a control box fixed to the helmet via a 1.8-meter cable, a removable strap over the head for comfort and stability, three pairs of vision lenses of different focal lengths, an HDMI cable, a USB cable, a DVI cable, an HDMI to DVI adapter and a 5-volt power supply, as shown in Figure 10. The helmet included a 7-inch (17.8 centimeters), 60Hz flat LCD screen with a resolution of 1280 x 800 pixels (around 720p high-definition resolution). The screen was divided into 640 x 800 pixels per eye, with a fixed distance of 2.5 inches (64 millimeters) between the centers of the lenses [20].

Figure 9 – Nintendo's Virtual Boy, released in 1995 [14].

In March 2014, Luckey sold his startup to Facebook for $2 billion. At the time of the purchase, Facebook indicated that *"Oculus is the leader in immersive virtual reality technology and has already built strong interest among developers, having received more than 75,000 orders for development kits for the company's virtual reality headset, the Oculus Rift. While the applications for virtual reality technology beyond gaming are in their nascent stages, several industries are already experimenting with the technology, and Facebook plans to extend Oculus' existing advantage in gaming to new verticals, including communications, media and entertainment, education and other areas. Given these broad potential applications, virtual reality technology is a strong candidate to emerge as the next social and communications platform"* [21].

Figure 10 – Detail of the components of the Oculus Rift [22].

After 2016, the VR headset industry became popular, and several companies released VR headsets. Among them, Sony PlayStation VR (PSVR), HTC Vive, Razer OSVR, Pimax 4K, Dell Visor and Lenovo Explorer as examples of headsets that require wired connection (See Figure 11). Qualcomm Snapdragon VR820, HTC Vive Focus, Oculus Go, Oculus

Quest and Lenovo ThinkReality VRX, are some examples of wireless headsets [23].

In 2019, Facebook released the Oculus Quest product, an evolution of previous Oculus products. Oculus Quest was Facebook's first standalone device, not requiring a physical connection to a PC [24]. The device included a pair of wireless touch controllers, for use in the hands. The success of Quest drove improvements that led to the development of Quest 2 in 2020, with better screen resolution, refresh rate, storage, and processing power. In 2022, the product was rebranded as "Meta Quest 2", aligned with Facebook's new strategy. Quest 2 uses a Snapdragon XR2 processor (a System-on-a-Chip or SoC from the company Qualcomm), has an LCD display in front of each eye of 1832 x 1920 pixels resolution, a refresh rate of 120 Hz and has four cameras, two of them oriented downwards, in order to visualize the position of the hands. In June 2023, Meta announced the evolution of Quest 2, the "Meta Quest 3", at a price of $500 [25]. The different versions of Oculus can be seen in Figure 12.

Figure 11 – Various VR devices.

Figure 12 – From left to right: Oculus Quest, Meta Quest 2, Meta Quest 3.

III. Augmented Reality

AR merges the real world with overlapping digital elements, enriching the user experience. Through devices such as tablets, smartphones or special glasses, AR offers an additional layer of information and interactive content about the physical environment. This allows to see contextual information in real time about objects or places, play games that integrate with the real environment, among other various applications.

The first AR device is shown in Figure 17 [26]. It consisted of a helmet, connected to a TX-2 computer. The helmet had a mechanical counterweight arm and used ultrasonic transducers to track head movement. The optical system consisted of two tiny cathode ray tubes used to present a virtual image in front of each of the user's eyes. A system of semi-transparent mirrors allowed the user to simultaneously see images of cathode ray tubes and objects in the room. An example of what the user saw is shown in Figure 14. A video of the device at work can be viewed at [27].

Figure 18 – AR helmet, developed in 13. On the left, the helmet is connected to a TX-2 computer. On the right, detail of the use of the helmet [26].

The term "Augmented Reality" was first introduced in 1992, by Thomas Caudell and David Mizell [28], who worked for the aeronautical company Boeing. According to Caudell and Mizell, *"This technology is used to 'augment' the visual field of the user with information necessary in the performance of the current task, and therefore we refer to the technology as 'augmented reality' (AR). For example, where a user looks at a workpiece and sees the exact 3D location of a drill hole is indicated by a bright green arrow, along with the drill size and depth of the hole specified in a text window floating next to the arrow"*.

Figure 14 – Observer's view of the 1968 AR helmet. The representation of a virtual cube is observed, superimposed on the real image of the background [27].

One of the first practical applications of AR was developed by Steven Feiner and his team, in the Knowledge-based Augmented Reality for Maintenance Assistance (KARMA) project in 1993 [29][30]. It was a prototype that used a transparent screen, mounted on the user's head, which helped in the maintenance tasks of a laser printer, as can be seen in Figure 15. It was implemented in C++ and ran under HPUX on an HP 9000 380 TurboSRX graphics workstation. The display server was written in C and ran on a PC based on a 50 MHz Intel 486DX processor, achieving 15 frames per second.

Steve Mann was one of the pioneers of AR. Since the beginning of the 1980s, he designed different equipment and systems of enhanced vision, or augmented reality, which he called "EyeTap Digital Glass", as shown in Figure 16 [31]. His vision was to have computers that could be wearable[1], without

[1] "Wearable" computers are smart electronic devices incorporated into clothing or body apparel.

wires connected to fixed computers [32]. This concept was not so easy to implement in the 1980s and 1990s, due to the technological development of the time (for reference, the first WiFi network prototype was developed in 1997, so Mann also had to develop the wireless communication system of his helmets).

Figure 15 – KARMA AR system from 1993. On the left is the technician with the AR glasses. On the right, the help image, superimposed on the user's real vision [30].

In the transmission of sporting events, AR techniques were introduced in 1998, with the addition of a yellow line to mark the position of a player or ball on the field [33], as seen in Figure 17.

For the creation of AR elements, Hirokazu Kato designed in 1999 a development kit which he called "ARToolKit". Its first use was related to the development of a video conferencing system with AR techniques, which used the superposition of virtual images in the real world. Remote collaborators were represented on virtual monitors that can be freely placed around in a user's virtual space. Users could view and interact collaboratively with virtual objects using a shared virtual whiteboard [34]. Images of the system can be seen in Figure 18. The ARTToolkit project is maintained as an open-source project, with commercial licenses available through the company ARToolWorks [35].

In 2009, menswear magazine Esquire was the first to use AR in printed media [36]. For its operation, a specific software, developed for the magazine, was required. The December 2009 issue of Esquire contained on its cover and in several internal pages, codes similar to the current QRs. Showing the code to the camera, animations associated with the texts were presented, superimposed on the image of the magazine taken by the PC camera. A video promoting the use of the software can be viewed at [37].

Figure 16 – Various AR devices designed by Steve Mann [31].

Figure 17 – First sports broadcast with AR, marking a yellow line superimposed on the image [38].

Figure 18 – Video conferencing system with AR, developed in 1999 by Hirokazu Kato. Left: a user in the virtual video conference. Center: AR representation of two users in the video conference. Right: an overlay of the virtual whiteboard shared with the AR elements [34].

In April 2012 Google announced its "Project Glass"[39], a device that consisted of a lens frame with a camera, a small screen on top of the right eye, and a touch bar on the right pin of the frame. At launch, the Glass team shared their hope that with Google Glass users will be able to search for information almost instantly to overlay it on what they're seeing and get richer insights into things around them, as seen in the concept video "Project Glass: One day..." [40]. Although initially released in prototype form for developers, the project was opened to the general public in 2013 with the "Explorer Edition" program [41]. Through this program, users could order a unit of Google Glass, at a cost of $1500, and experiment with this new technology. The "Explorer Edition" featured a futuristic and elegant design, with a lightweight frame and a small screen located in the upper right corner of the user's field of view. The display showed contextual information, such as reminders and navigation directions, without completely obstructing the user's view. In addition, it included a built-in camera that allowed taking photos and recording videos from the user's perspective. From the right side of the frame the user could interact with the device in a tactile way, sliding the finger horizontally, vertically, or with a small touch of contact. Voice command was also supported. Figure 19 shows the device of the "Explorer Edition" program.

Although the "Explorer Edition" program was a success in terms of generating interest and curiosity, it also faced criticism. Privacy was one of the main concerns raised by the public. Google Glass' ability to record images and videos without the knowledge of people close to it raised ethical and legal concerns about the use of the technology. These aspects, along with cost considerations, caused Google to halt the project in early 2015 [42].

In 2017, in a second attempt, Google made a relaunch of its Google Glass product, but this time, oriented to the business market. He called the new product Google Glass Enterprise Edition, an improved version of the one discontinued in 2015, with better camera, longer battery life, faster Wi-Fi and processor, and a new red light indicating video recording [43]. The objective was to gain users in the industrial market, where augmented reality glasses could provide a clear differential at work. In 2019 the product improved, reaching a price of $1000 each unit. However, after a few years of production, the end of sales of the Enterprise Edition of Google Glass was announced in early 2023, ending a decade of attempts by Google to position an AR product in the market [44].

Figure 19 –Google Glass Explorer Edition. Left: Device detail. Right: User's view for navigation directions [41].

AR had a peak of popularity in 2016, with the release of the game "Pokemon Go". It is a game that runs on a mobile device and combines elements of the virtual world of Pokémon with the physical location of the player in the real world. Using the mobile device's geolocation technology and camera, Pokémon Go allows players to search, capture, train, and battle iconic Pokémon characters in real-world environments. Players can explore the world around them and find *Pokemons* appearing on their mobile device's screen overlaid via the real-time camera. His popularity reached virtually every country, from the United States to Russia [45]. An example of the application is shown in Figure 20. Within a month of its launch, the app broke 5 Guinness World Records, including most revenue grossed by a mobile game in its first month, most downloaded mobile game in its first month, and the fastest time to gross $100 million by a mobile game [46].

In 2017, IKEA launched an AR-based app by the name "IKEA Place". This application, based on Apple's ARKit technology, allows customers to see the option of decorating their home with IKEA furniture before buying a product. According to IKEA, *"The app automatically scales products – based on room dimensions – with 98% accuracy. The AR technology is so precise that you will be able to see the texture of the fabric, as well as how light and shadows are rendered on your furnishings"* [47].

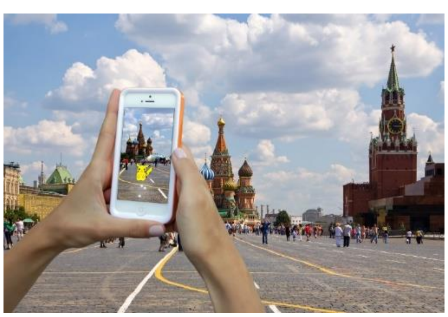

Figure 20 – Pokemon Go app in Moscow's Red Square [45].

Apple added in 2020 a Light Detection and Ranging (LiDAR) system on the back of the iPad Pro and iPhone Pro. According to its developers, it was the missing piece to revolutionize augmented reality applications. *"With the LiDAR scanner, professional cameras, motion sensors, advanced performance, professional sound, stunning Liquid Retina display and powerful apps, iPad Pro takes another step toward establishing itself as the world's best device for AR,"* Apple said [48]. LiDAR calculates the distance to objects up to 5 meters, can be used indoors and outdoors and works in nanoseconds. The new depth technology in iPadOS combines the depth points captured by the LiDAR scanner, data from both cameras and motion sensors with machine vision algorithms to recreate scenes in great detail. Developers using ARKit can include this technology in their applications.

In 2022 Google announced the possibility of search with "Live View". In the announcement, Google stated: *"Pick up your phone and tap the camera icon in the search bar to see nearby stores and other places like coffee shops, banks and ATMs. With AR-based directions and arrows, you can see which direction they are in and how far they are... Beyond showing where the places are, you can see in overlay key information about each place (such as whether it is open or not, how busy it is and what the price range is"* [49].

V. Mixed Reality

Mixed Reality (MR) combines elements of VR and AR to create hybrid experiences where virtual objects interact with the real environment realistically. By using advanced tracking and sensing technologies, users can interact with digital objects as if they were tangible, manipulating and experimenting with them naturally. MR has great potential in fields such as product design, medicine and architecture, where precise and realistic interaction with virtual elements can provide enormous value.

The term MR was introduced in 1994 by Paul Milgram, in the context of the *continuum* between the real and virtual world, as mentioned in the introduction [1]. However, it was not until the 2010s that the first MR-associated devices were developed. In 2010, Alex Kipman, an engineer at Microsoft, had a vision to create an MR device that would allow people to interact with the digital world in a more natural way. Thus began the "Baraboo" project, code name for the development of what would be Microsoft's "Hololens" MR lenses [50]. In March 2016, Microsoft officially released the first version of Hololens, aimed primarily for developers and companies interested in exploring the possibilities of mixed reality. The first-generation Hololens featured a limited field of view and was priced at $3000. It showed great potential in applications such as architectural design, education, and remote collaboration [51]. Figure 21 shows the first version of the Hololens. It was a wireless, self-contained, Windows-based device. Transparent lenses made it possible to see the real world, and on it, project digital images.

In 2019, Microsoft released the second version of Hololens, with a focus on the enterprise market. At a cost of $3500, the target audience in this opportunity were workers who require interacting with the physical world with their hands and having remote online assistance. *"If you think about 7 billion people in the world, knowledge workers are a huge minority"*, said Alex Kipman with the launch of this new version. For him, the workers who will use this device *"maybe people that are fixing our jet propulsion engine. Maybe they are the people that are* *in some retail space. Maybe they're the doctors that are operating on you in an operating room… The device is designed for 'first line workers'… People that have been, in a sense, neglected or haven't had access to technology [in their hands-on jobs] because PCs, tablets, phones don't really lend themselves to those experiences."* [52].

Figure 21 – Microsoft Hololens, 2016 [51].

Hololens 2 expanded the field of view and improved resolution, generating the equivalent of 2K monitors in each eye. The images are generated with Micro-Electro-Mechanical System (MEMS) technology, with 3 lasers (one red, one green and one blue) in each lens, as shown in Figure 23 [53]. The emissions of the lasers are combined and sent to a moving mirror ("Fast scan" in the figure), which oscillates at 12,000 cycles per second, generating a horizontal scan, and then sent to another moving mirror of 120 cycles per second ("Slow scan" in the figure), generating a vertical scan. The accuracy of the complete system is picometers (10^{-12} m). MEMS technology existed prior to the development of the Hololens, but had never been applied to a portable, miniaturized device with the precision required by this system. Beams of laser light are inserted into the lenses and guided through them, to finally be projected towards each eye, in order to obtain an appropriate three-dimensional image. This is done using waveguide technology called Surface Relief Grating (SRG). This technique allows the laser light beams to be guided through the lenses, to the specific point where they should be sent towards the eyes. At this point, by total reflection, the light is removed from the lens and directed towards the pupils, as shown in Figure 23. To accurately locate the position of the eyes, they are illuminated with infrared light, and captured with cameras to accurately track the location of the pupils (see Figure 24). This also allows ocular biometrics, with iris recognition.

Hololens also has two distance sensors, which use Time-of-Flight (ToF) technology. One of them is facing forward, in the line of sight, and another slightly downward, to track the hands, as seen in Figure 24. To capture ambient sound and be able to detect voice commands even in noisy environments, it has several microphones at different points on the device, including under the lenses themselves. Two speakers are located close to the ears, allowing to generate sensations of immersive sound.

The development and miniaturization of all these elements was challenging. Early prototypes were much larger and heavier, as shown in Figure 25.

Figure 22 – Microsoft Hololens 2, 2019 [52].

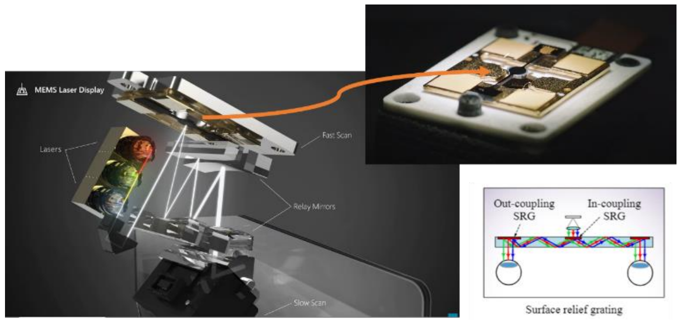

Figure 23 – Imaging system on Microsoft Hololens. On the left, the system of lasers and moving mirrors. On the right above, a detail of the moving mirror that generates the horizontal sweep. On the right below, a diagram of the operation of SRG technology. Based on [53].

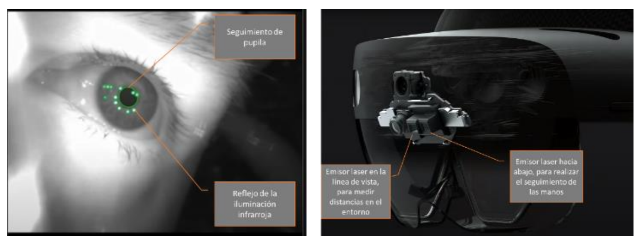

Figure 24 – Left: Eye tracking. Right: Depth and distance sensors. Based on [53].

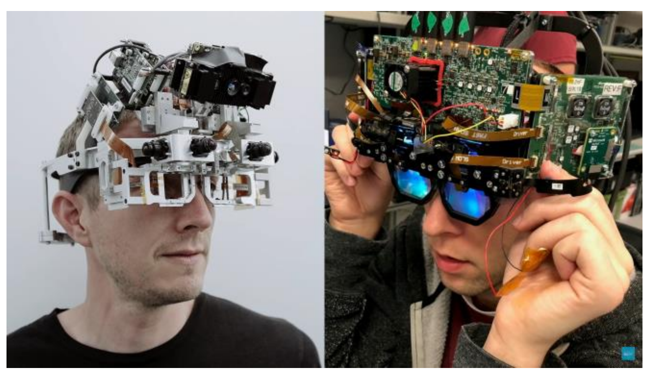

Figure 25 – Initial prototypes of Hololens 1 (left) and Hololens 2 (right) [53].

In June 2023 Apple announced its new product "Vision Pro" [54], defining it as *a revolutionary spatial computer that seamlessly blends digital content with the physical world, while allowing users to stay present and connected to others... Featuring visionOS, the world's first spatial operating system, Vision Pro lets users interact with digital content in a way that feels like it is physically present in their space"* [55]. Vision Pro features an ultra-high-resolution display system, with micro-OLED technology, which includes 23 million pixels on two screens (more than a 4K monitor on each eye). To allow user navigation and interaction with spatial content, these glasses include an input system controlled by the eyes, hands, and voice of the wearer. Users can navigate through apps just by looking at them, tapping with their fingers to select, moving their wrist to scroll, or using their voice to interact. Two amplifiers provide spatial audio, based on the geometry of the user's head and ear. Apple Vision Pro's eye-tracking system uses a ring of LEDs that project invisible light into the user's eyes and high-speed cameras to capture eye position and movement, serving as sensitive and intuitive commands. A new Apple-designed chip called R1 processes input from twelve cameras, five sensors and six microphones in real time. R1 transmits images to screens in 12 milliseconds (8 times faster than a blink).

The device, shown in Figure 26, must be connected to an external battery, which provides two hours of autonomy. They can also be connected to a Mac via USB-C and run continuously. It is expected to be commercially launched by 2024, at a price of $3500.

Figure 26 – Apple Vision Pro, 2023 [55].

V. Extended Reality Applications

AR, VR and MR transform the way we interact with the digital and physical world, and are being used in various fields, including entertainment, industrial and business. Some examples of industrial and enterprise applications are described below. This section is not intended to be exhaustive. The applications presented are just some of the possible ones, presented as illustrative examples of the potential of these technologies[2]. Entertainment applications are not included in this description.

A. Remote Technical Support

Remote technical support refers to a set of tools and methods used to provide technical assistance and support to troubleshoot problems remotely. Remote technical assistance allows experts to access and collaborate with on-site personnel, using AR or MR technologies. It is usually based on the use of glasses, helmets or mobile devices by on-site personnel, on which remote experts can see what is happening, and interact by overlaying images, presenting manuals or directions to on-site personnel. This type of support is especially useful in situations where response time is critical, or when resources or technical expertise are not available on-site. It saves time and travel costs, while providing a quick and efficient solution to technical problems.

Microsoft has developed the "Dynamics 365 Remote Assist" product, which allows to combine the Hololens with the Microsoft Teams collaboration product [56]. Using Dynamics 365 Remote Assist, a technician can contact an expert and interact online through the Hololens, as shown in Figure 27.

Figure 27 – Microsoft Remote Assist. A local technician is assisted by a remote expert. [56].

The Kiber company offers a helmet, "Kiber 3S", with AR techniques [57]. It is an industrial personal protection helmet, equipped with the necessary technology to provide remote online assistance in risky, complex or dangerous environments. It features a front-facing camera and two high-definition displays, which are located slightly above the line of sight, in front of each eye, as shown in Figure 28. On these screens, the technician on site can see, superimposed on the camera's vision, the indications of a remote expert. As a complementary element, a thermal camera is offered, which can also be monitored by the remote expert.

For the medical area, the company Vuzix offers the product M4000 [58]. A monocular MR device, with a transparent screen that is located in front of the user's (in this case, a surgeon's) view. A remote expert sees on his monitor the same as the local surgeon. With a camera appropriately placed on a model of the patient, the expert can give, with his hands, precise indications to the surgeon, who sees them on his transparent screen, superimposed on the real patient, as shown in Figure 29.

Figure 28 – Kiber 3S. A local technician wearing an industrial helmet is assisted by two remote experts. [59].

[2] The products and applications mentioned are only examples, and do not represent any type of relation of the author with the manufacturing or developing companies.

Figure 29 – Vuzix healthcare. A surgeon is assisted by a remote expert [58].

B. Guides for industrial works

Guides for industrial works with AR or MR are tools that combine information and visual instructions, in real time, with the physical work environment. These guides allow to overlay digital elements, such as text, images, graphics or videos, in the user's field of view, while performing their tasks. Work guides can include step-by-step instructions, visual indicators, technical data, reference points or safety warnings, all overlaid and contextualized to the physical environment in which the worker is performing the job. Operator interaction is intuitive, whether through gestures, head movements, voice or special input devices such as controllers or touch screens.

Microsoft proposes its product "Dynamics 365 Guides" [60]. An expert can define aids, work guides, warnings or any necessary information, in a graphical and 3D environment. In the work environment, QR codes are placed on the elements for which the guides are available. When scanning the QR, Hololens presents the operator with 3D visual guides about the tasks to be performed, directly over the corresponding physical elements, as shown in Figure 30.

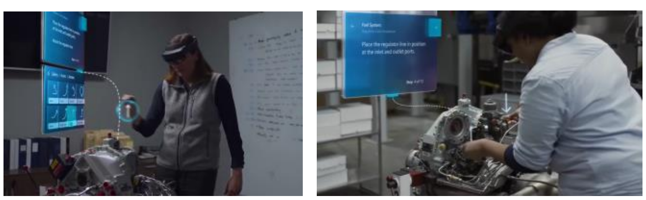

Figure 30 – Microsoft 365 Guides. An operator performs industrial tasks with the support of contextual, 3D work-guides directly superimposed on the physical elements [60].

The company TeamViewer promotes its product Frontline xPick, a software application designed to assist in logistics activities [61]. Using helmets or AR glasses from various manufacturers, it provides automatic help on scanning, picking and packing activities. With AR techniques, employees are told where to pick up each product, where to take it and how to pack it. An example, of the implementation of this application in the logistics center of the Samsung company, can be seen in Figure 31 [62].

Figure 31 - Frontline xPick application, applied to Samsung's logistics center [62].

C. Industrial, civil and architectural engineering design

XR technologies have significant applications in industrial design, civil engineering and architecture. These technologies allow engineers and architects to visualize and present their designs in a more realistic and immersive way. With AR, 3D models can be superimposed on top of the physical environment, making it easy to visualize what a project will look like in a specific location. VR, on the other hand, provides a completely immersive experience, where designers can explore and present their designs in realistic virtual environments. On the other hand, these technologies offer the possibility of evaluating and testing designs before their physical construction. Engineers and architects can interact with full-scale virtual models in a virtual environment, allowing them to identify potential problems and make changes before the construction stage.

The EyecadVR application allows to import any architecture design in standard format (such as CAD or BIM), configure or select different types of materials and present the 3D model in a virtual world, projected on VR headsets from different manufacturers [63]. In the created virtual world, it is possible to change skins, materials, or designs, as shown in Figure 32.

Figure 32 - EyecadVR application [63].

An example of VR applied to industrial design is the product "AR 3S" of the company Holo-Light [64]. "AR 3S" allows to import original 3D CAD drawings and visualize them in a virtual world. Using various tools, users can work with 3D content and combine physical parts with virtual objects. Figure 33 shows an example of the application, in an automotive design case.

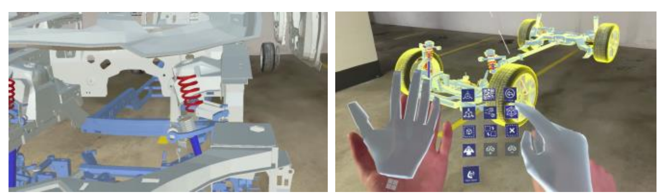

Figure 33 – Holo-Light AR 3S application, applied to automotive design [64].

D. Customer Service

AR and VR are also being used to improve customer service and user experience. For example, some companies are using AR and VR to show their customers how their products would look in different environments and colors, while others are using VR to offer their customers virtual tours inside their products, among other applications.

IKEA has developed the IKEA Place app, which allows shoppers to use AR with their smartphone camera to place furniture in their homes, so they can visualize exactly how the item will look in their environment, as shown in Figure 34 [65].

BMW allows car buyers to enter showrooms and customize cars with different colors or styles using their tablets or phones, using AR [66]. They can also put on virtual reality glasses and experience what it's like to drive cars, so they understand their options and can make the preferred decision for their new vehicle.

Figure 34 – IKEA Place app [65].

H&M introduced its "Metaverse Design Story collection" line in January 2022 [67]. Digital fashion spans the entire spectrum of traditional fashion, from casual T-shirts to elegant dressing. However, these clothes are not physically produced or tangible in any conventional sense. Instead, they are manufactured using animation and 3D design software, allowing people to "wear" these digital sets through avatars, within a digital world, generated with VR and AR. An example is shown in Figure 35.

Figure 35 – H&M's digital fashion designs, which can be worn in an AR or VR world [67].

E. Immersive meetings

With the announcement of the Metaverse by Facebook in 2021 [68], immersive meetings are starting to develop. To participate in these meetings, participants must wear VR headsets. The meetings in this virtual space are highly collaborative, where avatars of each participant interact, walk through the virtual space, write on shared whiteboards, see in three dimensions, among other interesting aspects. An example is showed in Figure 36.

F. Education

XR in education allows for a number of didactic activities. With VR headsets, concepts can be visualized in three dimensions. With AR techniques, the classroom can become a virtual museum, or paper books can include multimedia content, accessible from any smartphone. These technologies can be applied at all levels of education, from primary school to university. An example of the possibilities is Harvard University's "Giza Project" [69]. This project provides access to the largest collection of information, media and research materials ever assembled on the pyramids and related sites on the Giza Plateau in Egypt, using 3D technologies that can be accessible with XR.

VR headsets also allow to participate remotely in courses, in an immersive and interactive way. Unlike classic video conferencing applications (such as Zoom or Teams, among others), XR techniques allow students to live an educational experience "as if you were present". An example of this is seen in Figure 37, where several graduate students participate in an immersive class, in an experience conducted by IEEM business school and Quantik Labs in 2023 [70].

Figure 36 - Participant of an immersive meeting, writing on a shared whiteboard. Left: The real-world participant. Right: View of the participant in the virtual world.

Figure 37 – Graduate VR class experience. Up:, three of the students participating with their VR headsets. Down: the immersive experience in the virtual classroom.

VI. Conclusion

XR has experienced significant growth in recent years and is expected to continue its evolution in the future. As underlying technologies advance and become more accessible, XR has the potential to continue to transform numerous aspects of our lives, from entertainment and education to work and healthcare. XR-related technologies are advancing rapidly, along with growth in processing power, device miniaturization, artificial intelligence and autonomy in power supply. All this combined

suggests that XR devices and applications will become increasingly accepted and accessible.
The further development of current techniques and the inclusion of new technologies will allow unprecedented experiences. For example, the so-called Diminished Reality (DR) is a technique in development that allows *to remove* elements of the visual field selectively, and eventually replace them with synthesized objects. This requires reconstructing parts of the scene, which is currently possible thanks to generative AI technologies and advances in real-time processing. There are also developments to incorporate other senses, in addition to vision and hearing, known as *mulsemedia* (multiple sensory media). These new techniques promise to enrich the quality of the experience by adding tactile and olfactory effects [71].

Hardware devices are expected to reduce their costs, thus enabling greater adoption in the market. Along with this, XR techniques are likely to be increasingly included in social media applications, such as Facebook, Instagram and Twitter, generating more adoption and demand.

Interoperability and quality of experience are still a challenge for XR. The International Telecommunication Union (ITU) has created in December 2022 a Metaverse Focus Group (FG-MV) [72]. Its objectives include identifying and studying enabling technologies for standardization purposes, including multimedia, network optimization, connectivity, interoperability of services, security, protection of personal information and quality, among other aspects of XR. In July 2022, ITU standardized recommendation P.1320 "Quality of experience assessment of extended reality meetings" [73]. The objective of this recommendation is to establish the human, context and system factors that can affect the quality of the experience in XR virtual meetings, and to identify quality assessment metrics in these scenarios. FG-MV and the recommendation P.1320 are the first approaches to interoperability and quality measurement standards for XR applications.

XR technologies have transformed the way we perceive, interact and experience reality. VR, AR and MR have pushed the boundaries of our possibilities, taking us beyond what traditional technology had previously allowed. As these technologies continue to advance, exciting new opportunities open up in fields such as education, medicine, logistics, design, entertainment, and many more.

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