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Virtual Reality

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Popular media and recent consumer products give the impression that virtual reality (VR) is mostly about being tethered to a computer with a head-mounted display (HMD) covering the face, headphones over the ears, and some sort of controller in either hand for interaction. While this is indeed one valid incarnation of a VR system, it is not the only one. VR can be defined fairly broadly as synthetically generated sensory impressions (e.g., video, images, sound, touch) that are intended to immerse the users in an artificial, simulated, and interactive environment. This entry defines VR and discusses its history, hardware, and applications.

VR Defined

With vision being our dominant sense, it is no surprise that most VR solutions and research have a strong focus on the display technology (e.g., in the form of an HMD, where the presented images are adapted to head motion to give the impression of a continuous 360° environment, or as large screens that surround the user from all sides to achieve the same effect). To serve the auditory senses, usually, stereo or surround-sound speaker or headphone systems are employed. Touch is another important sense that can be stimulated through force-feedback systems to give the impression of a tangible virtual environment. Other senses (smell, taste) are also addressed; however, due to the technical complexity, the number of such solutions or research in these areas is proportionally much lower.

Interaction is a key component, allowing the user to navigate, react to, and influence the environment, which sets VR apart from a purely passive theme-park-like presentation of a movie.

VR is situated at one end of a continuous spectrum with augmented reality (AR) at the other end. VR is mostly characterized by a total exclusion of real-world stimuli (e.g., by using an HMD that blocks out any view of the physical environment) or by using a dedicated empty room. AR, on the other hand, is mainly defined by the necessity to see the surroundings for the virtual content to be overlaid on top of it.

History

On a pragmatic basis, the origin of aspects of modern VR could be traced back to the emergence of large-scale panoramic paintings of the 19th century. In 1793, Robert Baker purpose-built a panorama building in London that showed 360° paintings of Edinburgh and London landscapes on the surrounding walls, completely immersing the viewer, who stood on a central platform.

In science fiction literature, glances of modern HMDs can be found in Stanley Weinbaum's 1935 short story *Pygmalion's Spectacles*. The protagonist presents a device that can record a scene in a special liquid. To play the scene back in its full sensory richness, including sound, smell, taste, and touch, the user is required to put on a mask with goggles and a mouthpiece. This device would then immerse the subject's eyes in the recording liquid, thereby playing the scene back in its full detail.

In 1962, Morton Heilig patented a device called "sensorium," which was able to play back a wide-angle stereoscopic movie with stereo sound, provide haptic feedback through body tilting, and could generate wind and scents triggered by additional recording channels. However, due to lack of funding, it was never produced in larger numbers.

While the previously noted examples are precursors to today's VR technology and principles, they all lack the important aspect of interactivity to classify as full VR implementations. One of the first VR systems to fulfill all the aforementioned aspects is widely considered to be the "Sword of Damocles," which was developed by Ivan Sutherland at the Massachusetts Institute of Technology in 1968. In his quest for the "ultimate display," he connected a computer to a stereoscopic display unit, which was itself attached to a mechanism above that could track its movement. By adapting the shown image through mathematical principles of three-dimensional (3D) transformation and projection based on the position and view direction of the display, Sutherland was able to give a user the impression of viewing 3D wireframe models (e.g., a cube, a room, or a molecule floating in the room at a static position).

Given Sutherland's background, he approached VR from a scientific perspective. However, large parts of modern VR were also defined through the arts, specifically by the work of Myron Krueger. With his interactive installations METAPLAY (1970) and VIDEOPLACE (1975), he immersed users in a room with a large projection of an environment that would change in response to the user's actions, a concept he referred to as "artificial reality." In VIDEOPLACE, the images were controlled purely by a computer and also combined the interactions of two users, introducing social aspects to the experience.

Around 1985, VR gained commercial traction with the foundation of VPL Research by Jaron Lanier. The company developed VR-specific hardware such as the EyePhone, an HMD device; the DataGlove for gesture-based input; and the DataSuit for full-body movement input. VPL Research also popularized the term *virtual reality* in the context in which it is used today.

Until the end of the 1990s, VR gained public interest, fueled by movies, books, magazines, and media coverage of the subject. However, due to the technology not being of an acceptable technical standard with low resolution displays, low computing power, and most of all a lack of suitable applications, the VR movement peaked before the year 2000 and vanished from the consumer market. In the areas of military, science, and industry, the technology and software were still continually developed, but at a slower pace and less visible to the public.

In 2012, Oculus VR founder Palmer Luckey announced the Oculus Rift, a cost-effective version of an HMD that suddenly reignited the development of VR technology and applications for the consumer market. Since then, numerous related products have been introduced to the market (e.g., the HTC Vive, the Gear VR, or the Playstation VR). Compared with the technology of the 1990s, the display quality and comfort have improved greatly. Also, computing power has reached a level where interactive environments can be rendered with high quality and rich detail.

However, most important for the success of this third generation of VR technology is the introduction of software development and distribution mechanisms that allow applications to be built by everybody, not only by commercial companies. Through the Internet, it is easy to update and develop VR technology in close communication with the growing community. Software and technology details are kept open and publicly viewable. This creates fairly standardized programming interfaces and conventions that allow for a quick adaption of one application for more than one VR system. Within a very short time, major 3D application development tools such as Unity3D or Unreal Engine had in-built VR system support.

With respect to distribution, Internet-based marketplaces for applications allow users to choose from a large selection of applications that render VR systems attractive for the consumer market. Games form a large part of these applications, but increasingly, short stories, experiences, and creative applications such as 3D painting and 3D modeling programs have started to appear.

In addition, Internet connectivity allows for the development of social experiences, for example, virtual chatrooms and spaces where users can talk, interact, use body language naturally, cocreate virtual objects, and collaborate on projects. Not surprisingly, Facebook, the largest social network platform at the time, acquired Oculus in July 2014 and started development of a VR version of their social network.

Hardware

3D Vision

In its simplest configuration, it is possible to present the visuals to the user as a 2D video (e.g., in desktop personal computer–based VR applications or, to increase the immersion, on large projection walls). Most VR systems, however, use the principle of stereo vision to create a 3D perception of the virtual content. To achieve this goal, the system has to effectively present two independent images to the user’s eyes, taking into account effects of the space between them on the view of a scene (e.g., parallax, occlusion, slightly different view angles). From these cues and additional aspects such as perspective, the brain is then able to reconstruct the 3D information of the scene.

To present an independent image per eye, several principles can be used. One common technique is the projection of the two images onto a common surface using polarizer filters. The user, therefore, has to wear glasses with matching polarizers to have each eye only perceive the correct one of those two images. Since this form of glasses do not require any active component, they are fairly inexpensive—the complexity lies in the precision of the optical filters. An alternative, but slightly more complex, principle is to rapidly alternate the projected images of the left and the right eye on the same screen, with active glasses blocking the view of the other eye accordingly. Both principles have the disadvantage of effectively reducing the brightness of the image by 50% but the advantage of allowing several users to see the same content in parallel (although, different viewpoints of each user are an issue).

A more individual solution is the HMD, where a small screen with projection optics is located in front of each eye (see Figure 1). Depending on the type of display, the user can be completely isolated from the surroundings or—using a see-through display—can have content overlaid onto the real world (the latter typically is now defined as AR). Usually, HMDs suffer from a tunnel-vision effect due to the limitations in optics and display sizes. As of 2017, most HMD technology allows for a field of vision of around 110°, whereas the human eye has nearly 180° of horizontal field of vision. Some HMD manufacturers, however, advertise 210°.

Figure 1 Virtual Reality Demonstration of Head-Mounted Display and Data Gloves

Source: National Aeronautics and Space Administration (https://commons.wikimedia.org/wiki/File:Head-mounted_display_and_wired_gloves,_Ames_Research_Center.jpg).

Note: Virtual reality gear can provide surprisingly realistic depictions using visual images, sounds, and movement and occasionally touch and smell as well.

Due to the nature of the images and the projection system, there are several problems to each of the previously mentioned display solutions. One of them is the fact that the human eye automatically focuses on an object based on its perceived distance. However, with a constant distance of the eye to the screen, this is problematic in VR and one cause of discomfort during longer exposure. One solution to this problem is the use of light fields, a technology that preserves not only color and brightness of each object of a scene but also the direction from where light reaches the eye. This allows for the user to flexibly choose a focus point instead of having only a fixed one.

3D Tracking

Regardless of the presentation technology used, an important feature for a VR system is that of head tracking. Depending on the movement of the user, the presented images have to change with respect to a new position of the eyes and—in case of HMDs—also with respect to the direction that the user is looking at. The early VR systems of the 1990s suffered from a relatively long delay between the actual movement of the device and the visual change in the presented images. This "motion-to-photon" latency is one of the main factors of discomfort in VR due to the temporal disconnect of the motion perceived by the vestibular organ and the change in imagery expected to be seen by the eyes. Often called "simulator sickness," this disconnect manifests itself as nausea and disorientation and can last for several hours after the actual VR experience. Modern systems attempt to counter this effect with high framerates (up to 120 Hz) and hardware and software optimizations (e.g., prediction and 2D warping of the image), to keep the latency below 20 ms, a time span accepted by the industry as below the perception threshold of a human.

Early systems such as the "Sword of Damocles" used mechanics to determine the movement and rotation of the user's head, which resulted in heavy and complex constructions that limited the freedom of movement. Later, magnetic technology allowed for more freedom and a larger space for movement but still required a tethered sensor on the headset. Ultrasonic tracking solutions exist but are not very common. Modern industrial VR solutions often use high-quality optical motion capture systems, where cameras track reflective markers on the glasses or the headset to track their position and orientation. Some consumer grade systems use one or more cameras to detect a specific pattern of LEDs on the headset for that purpose. Others use external laser projectors that generate a dynamic light field that the HMD and the hand controllers can detect and reconstruct their movement and position from. Most of the previously noted tracking solutions suffer from a certain delay in measurement, which is detrimental to the comfort of a VR system, specifically when using an HMD. In these cases, additional sensors can be combined to form hybrid systems, for example, with inertia sensors sensing acceleration quickly but requiring the optical system to compensate for their inherent drift.

All these systems require external active components around the HMD and are therefore called "outside-in" tracking solutions. Some alternative consumer systems use "inside-out" tracking, where all technology is in-built and the size and shape of the room and the user's position and orientation within it are determined without any other technical assistance.

3D Audio

In VR systems, the user moves and interacts in a 3D space; therefore, any audio representation needs to take this into account. When designing 3D scenes for VR, audio sources will almost always have a spatial position and acoustic properties such as range and directionality. In addition, the space has acoustic properties that influence the sound depending on the position and orientation of the user in the scene (e.g., reverb). Modern systems can use "dry" recordings of sound without any reverb or other effects of a space and reproduce them virtually in any acoustic environment (e.g., a cathedral).

The simplest way to present this audio content to the user is by stereo headphones that are coupled with a simulation of how the human ears would perceive the audio sources in the scene depending on their position and orientation. In its simplest form, this manifests itself in minute delays between the sound arriving at the left and the right ear, which the brain uses to determine the direction and distance of the source. In more complex systems, the effect of the shape of the ear, the ear canal, and the head is considered as well, rendering information of a sound source such as "behind" and "above" with greater detail.

When headphones are not an option, surround sound systems or more complex multichannel systems are used. Speakers surrounding the physical area of a VR system can reproduce sounds from different directions, albeit with some limitations to the positioning of sound sources. By using a large number of speakers configured as an array and wave field synthesis, these limitations can also be overcome, albeit with a trade-off in the form of more complex hardware and computational effort.

Acoustic systems also need to work with timing constraints that are much tighter than the tracking system. While the latency in the optical components needs to be less than 20 ms, it needs to be less than 1 ms for acoustic processing.

Controllers and Haptics

The hands are the main means of humans to manipulate their environment, which reflects in a large variety of hand controllers and research in the area of manual and gesture-based input. 3D-tracked joysticks, mice, or gloves can be used to point at 3D objects and to trigger interactions or events. Gloves and hand trackers also allow for fine-grained input from the fingers (i.e., through gestures such as pointing, pinching). Modern controllers include complex control elements that are found in game consoles such as trackpads or thumbsticks to utilize the dexterity of individual fingers.

Haptic feedback from the VR system to the user’s hand or fingers can be implemented in simple ways such as vibration motors or small actuators that apply a small impulse force to the fingertip or to other parts of the hand or the body. This is sufficient to give feedback about triggered actions or other events but not suitable to convey shapes or more complex forces in the simulated environment.

More complex haptic-feedback systems with motors and pulleys, hydraulic elements, or other forms of actuators are capable of applying sufficient force to prevent the user from penetrating a virtual object, therefore rendering an illusion of an actual solid (or deformable) virtual object. Such systems are widespread in surgical simulators, where a high realism of the actual feeling of manipulating soft tissue is vital for the realism and the training effect.

Force feedback can be extended to affect the whole body by using motion systems that can be accelerated in all directions and tilted around all axes (e.g., robot arms or parallel robots). These systems can simulate the behavior of large vehicles in motion, such as cars, ships, or planes. However, with the considerable technical complexity and control mechanisms comes a high cost, which makes it unsuitable for the consumer market.

Extension of force feedback or other haptic sensations to the body can be achieved by devices that address specific additional areas (e.g., the chest through wearing a vest or the whole body by wearing full suits that are equipped with sensors and actuators). Again, increased complexity and cost are trade-offs for an increase in sensation and immersion.

Control of locomotion in VR is also a problematic issue, mostly due to limitations of the physical space (e.g., room size, length of cables, or limited range of tracking sensors). Solutions for creating larger physical movement space involve mechanical treadmills or low-friction footwear to keep the feet in one place but allowing for walking or running leg movement.

When wearing a headset with total visual isolation from the surroundings, it is also possible to warp and distort the visual representation of movement and space and thereby redirecting and reorienting the user to make a small physical space virtually appear much larger. However, such manipulations must be done below a certain perception threshold to go unnoticed and without causing adverse effects such as nausea.

Miscellaneous

An ideal VR system would engage all five senses of the user to create the effect of full immersion. Research and technologies to address sight, sound, and touch are fairly widespread, while smell and taste are not. Morton Heilig's Sensorama implemented smell through controlled opening of containers with olfactory materials. This principle is also used by commercial solutions (e.g., in a mask that is worn in addition to an HMD and can produce smells from a set of vials containing olfactory liquids).

Taste can be simulated through electrical stimulation of specific areas of the tongue; however, this is a fairly intrusive principle. Electric stimulation in general might be a future solution for all senses, eliminating the need to produce a certain stimulus physically and instead generating it by direct excitation of the associated part of the nervous system.

VR Applications

With access to funding sources that allow for acquisition of the initially expensive VR hardware, it is not surprising that military applications were developed fairly early in the history of VR. The visually coupled airborne systems simulator was designed at the beginning of 1977, using an HMD with head and eye tracking to present the full view from the cockpit of the simulated plane to the pilot. This principle can easily be extended to other forms of vehicles and positions (e.g., infantry, paratrooper, tank driver, or gunner). By using networked VR systems, it is also possible to train teams and to implement large-scale virtual exercises.

Using large-scale projection screens, it is possible to mix real objects such as equipment, props, or medical practice mannequins with the virtual simulated environment, for example, a city scene with enemy soldiers or vehicles that react to the trainees through 3D tracking of their positions, movements, and training weapons, which are also functioning as input controllers. Such a training can also be applied to the training of first responders, or to scenarios such as large-scale emergencies or catastrophes, where the training objective is managerial rather than procedural.

In the area of medicine, VR simulation has found a large market in training devices for surgery (e.g., endoscopic procedures), where the realism of the visual representation of the simulated operation field are as important as the haptic feedback through the manipulators that are used as input and output devices simultaneously.

In psychology, the capability of VR to present content in a controlled environment with the option to adjust the amount and intensity of the experience is an important factor. One example of application is exposure therapy for people experiencing conditions such as posttraumatic stress disorder or phobias. Traumatizing events or phobia-triggering situations can be re-created in a safe environment with full control over the duration and intensity and under constant supervision of the therapist. Information from head and eye tracking and other sensors also allows for additional diagnostic input.

In medicine, VR scenarios can be used to support treatment or healing processes. While changing dressings of burn wounds, the patient can be distracted by presenting a VR winter landscape where snowballs can be thrown at snowmen. The perceived duration of chemotherapy can be reduced through VR experiences that distract from anxiety-inducing stimuli and assist with relaxation. In rehabilitation (e.g., after strokes), VR technology can be used to help with exercises.

In science, VR is used mainly due to its capability to render and explore 3D structures (e.g., in visualizations of subatomic structures, neural networks, geological data sets, atmospheric phenomena, or astronomical models). Most VR systems in this context are 3D projection screen-based and tracking systems for controllers and user position, usually referred to as cave automatic virtual environment. Similar configurations are used not only in engineering for planning and construction but also for 3D visualization of dynamic behavior (e.g., of air and liquid flow, aerodynamics, forces, mechanical simulation).

In the consumer market, VR has again started to gain attraction due to a decrease in price, increase in ease and comfort, and a comprehensive range of applications. A large proportion of these are games, but developers are increasingly discovering alternative uses for VR systems. Initially, first-person-perspective games seemed an obvious choice for being adapted to VR, but it quickly became apparent that the differences in interaction, intensity of the experience, and necessary changes of gameplay mechanics severely complicate this adaption process. New “languages” of storytelling and different approaches to user experience design have to be explored for VR to become a lasting mainstream medium. One example of emerging VR genres is experiences that put the user into somebody else’s situation to evoke a sense of empathy.

The arts have always embraced new technology, and in the case of VR, it significantly shaped its history. Artistic VR applications have always stretched the limits of creation and presentation of content, and with a growing variety of creative applications, such as 3D painting and animation tools, there is much future potential.

Last but not least, the advertisement industry uses VR for presenting products in new and attractive ways (e.g., a virtual test drive to get an impression of the new car or previsualizing the look of new furniture in the lounge). Again, the ability to distribute VR applications through the Internet allows for fairly complex product presentations to be run from home.

See also Augmented Reality; Internet Advertising; Internet Gaming; Video Games and the Internet

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