Chapter 3
Metaverse and Immersive Interaction Technology

The rise of the metaverse concept is an opportunity and a challenge for developing its core technologies. Among the many technologies, immersive interaction technology is a significant one. This technology has been widely used in paramedicine, industrial design, VR games, and 3D movies. This chapter mainly introduces the concepts, theoretical foundations, and applications of immersive interaction technologies.

3.1 Introduction of Immersive Interaction Technology

As the concept of metaverse spreads, more people are looking at the field of immersive interaction technology. Immersive interaction technology can make the metaverse more realistic, thus allowing people to experience the world better; therefore, immersive technology is the core technology of the metaverse. Immersive interaction technologies include many aspects, and currently commonly used technologies include Virtual Reality (VR), Augmented Reality (AR), Mixed Reality (MR), and Extended Reality (XR). VR can realize the input and output of information in the metaverse by taking over the complete sense of sight, hearing, touch, and motion capture to bring people an all-around immersive experience. AR technology superimposes a layer of virtual information on top of the real world, but interaction is not yet possible at this stage. MR mixes the virtual with the real, creating virtual objects that can interact with the real environment by projecting a light field on the retina, enabling partial retention of the virtual image and the ability to switch freely with reality. At last, XR includes all three kinds of "reality" (AR, VR, and MR), and it is also increasingly mentioned.

Humanity's mental expansion of the real world is constantly evolving, from handwritten words and hand-drawn pictures in the past to movies, TV, and today's PC games and VR games. Virtual reality compensation theory and world simulation

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theory are important foundations that support this expanded journey. Virtual reality compensation theory means that what a person lacks in the real world will try to make up for in the virtual world. When possible, they will achieve compensation in the virtual and real worlds. On the other hand, the world simulation theory assumes that a civilization's impulse to create virtual worlds to be compensated is eternal, so long-term development will inevitably create a virtual world, and a higher level designer may create the world in which it is itself located. Jean Baudrillard's simulacrum theory divides the history of human simulation into three stages: counterfeit, production, and simulation.

Counterfeit The real and the virtual are still distinguishable, and the real is higher than the virtual. This stage follows the law of natural value, believes that things in the real world are valuable, and pursues to make imitations that simulate and replicate nature and reflect nature.

Production The status of real and virtual things gradually tends to be equal. This stage follows the laws of the market and aims to win market value. The mass-produced imitations form a similar relationship with the real copies.

Simulation Real and virtual are confused with each other. This stage follows the law of structural value and aims to make the simulation and the real give an indistinguishable experience. In the simulation stage, the simulacrum is produced through reproducible technology, and the real object is thus defined as "something that may produce an equivalent copy." As the replication process advances, the simulacrum assimilates reality into itself, and the boundary between the two disappears.

From this theory, it is clear that the human quest for virtual reality is constantly moving forward, and Fig. 3.1 is ample evidence of the continuous spiritual expansion of virtual reality in the way humans themselves.

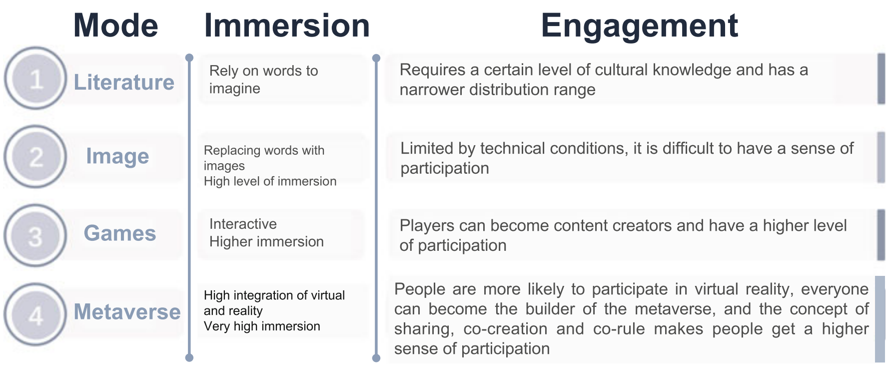


Fig. 3.1 Stages of mental expansion to the real world

3.1.1 *Virtual Reality (VR)*

Virtual Reality (VR) technology involves mainly computer, electronic information, and simulation technologies. VR creates an entirely virtual environment by isolating all real-world images through the device. Users can experience 3D virtual immersion through VR head-mounted displays. Virtual reality technology uses computers to generate simulated environments and immerse the user in them. It uses electronic signals generated by computer technology, combined with various output devices, to transform real-life data into virtual images that people can see. These images can be real objects in reality or substances that are invisible to our naked eyes, and 3D models will represent these images. Because these images are not something we can see directly but are simulations of the real world through computer technology, they are called virtual reality. Virtual reality enables users to be fully immersed in a virtual world. A proper virtual environment should be able to simulate the five human senses (taste, sight, smell, touch, and hearing), but this is not yet entirely possible with current technology.

Since the Homo sapiens brain has evolved over 200,000 years, the human instinct to react to the outside world has largely taken shape, so trying to use virtual reality to trick the eyes is a very challenging task. If we put our eyes close to the screen, we may still see the real world outside the screen through peripheral vision, while if the eyes are too close to the screen, they cannot focus and thus cannot see objects.

VR devices have also undergone several iterations of updates:

CardBoard To allow the left and right eyes to see the standard picture, the image is split on the left and the right, and the images seen by the two eyes are slightly different after the split screen, which can produce a sense of three-dimensional distance, and the screen can be pushed up to a distance of one meter through a convex lens, but doing so distorts the picture and creates colored edges. This negative effect is well offset by making the image anti-distortion and the edge anti-color. To solve the problem of other objects in the field of view, a cardboard box can be used to cover the lens to obscure the excess vision. Based on the above principle, Google launched the first generation of simple VR devices, CardBoard.

VR All-in-One Headset Although the CardBoard has met the basic needs of a VR, this simple box does not meet the needs of consumers to wear. For this reason, some researchers began to improve the CardBoard, replacing the cardboard box with a sponge and rubber. Due to the different facial structures of men and women and to meet the needs of near-sighted people, the new box added the eye distance adjustment function. But this box requires the phone as part of the VR, also known as all in ones, such as Xiaomi VR eyes and Storm Magic Mirror.

However, this technology has many shortcomings. First, the GPS accuracy of the phone is too low; after the person is wearing VR glasses, the picture cannot change in real-time according to the person's movement. Second, this stage uses air pressure sensors to measure height, which will lead to too much deviation, and the size of the person cannot be known in the virtual world, which leads to the height of the person cannot be measured with the phone. When a person squats or stands up, it is impossible to know how far the ground is from the person and to see the movement of the person's limbs. The only thing the phone knows is the direction determined by the gravity accelerometer and compass, as well as the change in angle through the gyroscope, allowing real-world objects to change according to the movement of the player's head. When a person wears VR, a shift in the curve occurs at a fixed position, and the phone needs to perform calculations to render a real-time picture. This has a slight delay from when the human brain thinks the change should occur, and the resulting vertigo is enough to make the person feel uncomfortable.

VR Splitter Some manufacturers detached the phone from the VR device and this improved the portability of the device, but in terms of performance, it still belonged to the lightweight products, as its play and VR all-in-one machine are almost the same. Some examples are products such as the Piconeo, GearVR of Samsung, etc.

PC VR VR all-in-one and VR splitters are based on the mobile processor; to get a higher resolution, refresh rate, and more accurate tracking accuracy, it is necessary to add a high-performance PC, not only that but also need to use multiple high-speed cameras to track the player's movements, and the most famous products are HTC VIVE.

HTC VIVE is equipped with a Valve controller and Lighthouse positioning system and provides two screens with 1200Œ1080 pixel resolution and 90 Hz refresh rate, bringing users ultra-low latency and a fast gaming experience. The steam platform offers a rich game ecology, giving consumers an excellent experience. Still, PC VR is usually the choice of high-end gamers and some players with professional needs; relatively speaking, its price is also costly.

Home Mainframe VR Microsoft and Nintendo have not launched products in the field of home consoles, Sony relies on years of technical accumulation, and the game ecology launched PS VR. With the support of the performance of the game console, the camera monitors the colored light ball held by the player's hand to track its position and movement. But unlike the PC platform, the independence of Sony's game ecosystem dictates that game content is not as rich as PC VR.

Figure 3.2 shows the VR products launched by each company.

3.1.2 Augmented Reality (AR)

Augmented reality (AR) technology combines virtual objects with the real world by superimposing images on the real world and using holograms. Google first developed AR glasses, and each lens has a built-in projector that combines reality with the virtual. It functions similarly to a smartphone placed on glasses. Essentially, AR and VR are similar; in the long run, they are products that overlap and interact with reality and the virtual. Unlike VR, AR is an augmentation of the real world. On the other hand, the core structure of VR is mainly based on

Fig. 3.2 VR products: (**a**) CardBoard, (**b**) Xiaomi Split VR box, (**c**) Samsung Gear All-in-One VR, (**d**) HTC VIVE, and (**e**) PS VR

the environmental simulation system, which completely abandons the real world and strives to construct the perfect virtual world that can deceive human senses. However, it is not yet possible to completely confuse the virtual world with the real world at the optical level.

However, they cannot be confused at the optical level, and there is a transition phase. From a technical point of view, in the roadmap of VR and AR, it can be seen that the underlying chip is Qualcomm, the algorithm is a combination of visual technology AI, and the content engine is Unity. AR has higher requirements for optics and algorithms. Optically, lens semiconductor optical technology must be implemented, and algorithms require technologies such as large-scale positioning. Popular AR applications include Pokemon Go and Snapchat's AR bit-emojis. Compared to VR, which is a cumbersome device to wear, AR has a more extensive user base and more application scenarios. Various practical applications in medicine, education, and industry have proven that AR has a more profound impact on humans as a tool.

AR devices are divided into two categories: AR phones and AR smart glasses. Apple has been in the AR space for a long time, acquiring Metaio in 2015 and developing it into ARKit. At the WWDC 2017 developer conference, the WWDC2017 developer conference, Apple provided an interface for iOS 11 through ARKit. Its software solution using computer vision technology enables intelligent understanding of the real environment by combining cameras, gyroscopes, and accelerometers. After two iterations, a live demo of the Minecraft AR game was completed at WWDC2019 on ARKit3, which supports live capture and full-body motion capture. In a subsequent update, LiDAR was added to reduce the hardware configuration requirements.

Fig. 3.3 AR cell phone and AR smart glasses devices: (**a**) Apple AR Cell Phone App and (**b**) ODG's AR Glasses

AR smart glasses, such as ODG, Darqri, Vuzix, Epson, and Snapchat, have launched their products in the enterprise or consumer space. Osterhout Design Group is one of the major U.S. military companies, founded in 1999 as a technology incubator. It currently focuses on AR headsets with Snapdragon processor's 1080 pixel OLED displays. Its stand-alone computer glasses and "see-through" 3D displays have a broad market. The navigation system and inertial sensing technology allow users to experience telepresence, remote maintenance, and repair and perform well in industrial production (Fig. 3.3).

3.1.3 Mixed Reality (MR)

Mixed reality (MR) is a new visualization environment resulting from the fusion of real and virtual worlds, where real and data entities coexist while being able to interact in real-time. In other words, "images" are placed in real space, and these "images" can interact with familiar objects to some extent. MRs key feature is that virtual and real objects can interact in real-time. MR is between augmented and virtual reality, blurring the boundary between virtual and reality, integrating digital virtual objects into the real world for interaction. In the virtual world, real objects appear in the form of virtual reality.

Conceptually, MR is similar to AR, but MR allows interaction with the real world and instant access to information. Traditional AR technology mainly uses prism optics to refract real images, but the perspective is not large, and the clarity is not high enough. The new MR technology, to bring a better immersive interactive experience, may choose helmets, mirrors, transparent devices, etc., as the carrier of its technology in addition to glasses and projectors. One of the more technologically advanced and versatile MR devices available today is Microsoft's HoloLens line, which includes HoloLens 1, released in 2015, and HoloLens 2, to be released

Fig. 3.4 MR devices: (**a**) HP MR, (**b**) Samsung Genron MR, and (**c**) HoloLens 2

in 2019. Users can interact with holograms through gaze, voice, and gestures. In addition to Microsoft's HoloLens family of MR devices, there are well-known MR devices such as the Samsung Gentoo MR and HP MR (see Fig. 3.4).

HoloLens 1 is the first holographic computer that is completely cable-free. HoloLens 2 builds on HoloLens 1 by increasing the field of view, enhancing camera clarity, and adding eye-tracking capabilities. HoloLens primarily targets the B-side of the market and offers a military version for the U.S. military. HoloLens 2 is available in the UUSA, Canada, China, Japan, Korea, and several European countries. The main development plan for Microsoft's next generation, HoloLens 3, is to improve immersion, reduce its weight and power, and thus increase social acceptance.

3.1.4 Extended Reality (XR)

Extended reality (XR) refers to the combination of real and virtual through computers to create a virtual environment that can be interacted with by humans and machines, which is also the collective name for various technologies such as AR, VR, and MR. XR is a rapidly growing field and can be used in many applications such as environmental, marketing, real estate, education and training, and remote work.

The specific relationship between XR and various technologies such as AR, VR, and MR is shown in Fig. 3.5. Integrating the visual interaction technologies of the three provides users with a sense of "immersion" that seamlessly transforms between the virtual world and the real world. XR technology is mainly capable of visual, auditory, tactile, olfactory, and gustatory sensory stimulation, as well as somatosensory stimulation (operating interaction through changes in body movements) and brain–computer interface (establishing a new communication and control channel between the brain and the external environment that does not rely on peripheral nerves and muscles, thus enabling direct interaction between the brain and external devices). XR technology can benefit some emerging fields, such as virtual digital humans, simulation robots, brain–computer interfaces, etc.

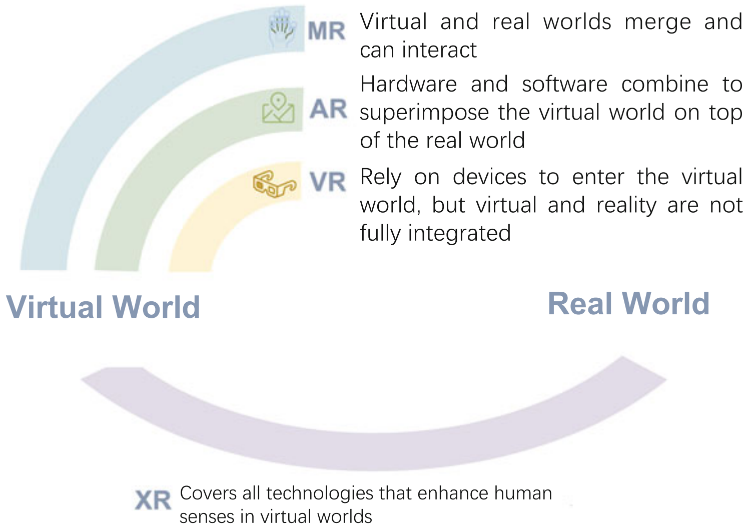


Fig. 3.5 The relationship between XR, VR, AR, and MR

3.2 Support and Development of Immersive Interaction Technologies

Immersive interaction cannot be achieved without the technology development and support behind it, such as image display principles, as well as data visualization (expressing data graphically), computer graphics (3D models, building more realistic models), and other supporting technologies (backend infrastructure, 5G/algorithms and algorithms/cloud computing, underlying architecture, etc.). The principles and implementation of these technologies are described below.

3.2.1 Image Display Principle

The image display principle relies on a head-mounted device, the core of which is the head-mounted device screen, containing two basic elements: optics and image display.

1. Optics

The total angle of the image both eyes see is called Field of View (FoV). The human horizontal binocular field of view is 200 degrees, with binocular overlap accounting for 120 degrees. Binocular overlap is significant for the establishment of stereo vision. Unlike the horizontal field of view, the vertical field of view is about 130 degrees, as shown in Fig. 3.6.

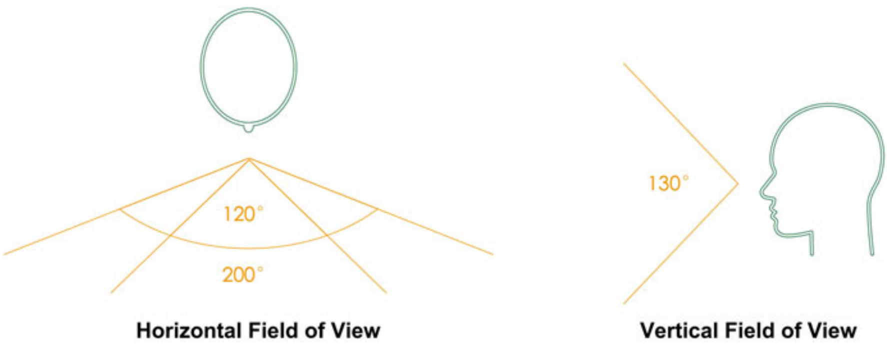


Fig. 3.6 Horizontal and vertical Field-of-View angular maps for human

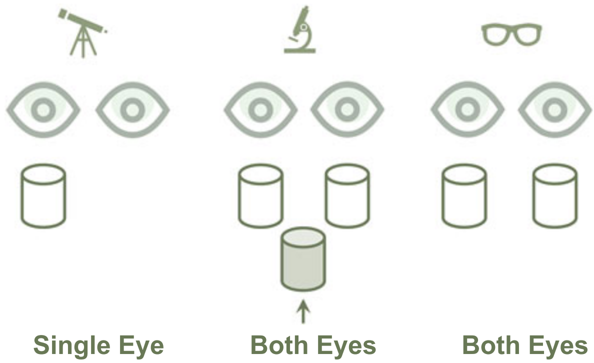


Fig. 3.7 Immersion effects when using different devices

Interpupillary Distance (IPD) is the distance between pupils and is related to race, gender, and age. An improper IPD may cause lens distortion or lead to eye strain and headaches. The minimum IPD for children is about 40 mm, while the average adult IPD is about 63 mm. As shown in Fig. 3.7, each human eye obtains depth of field and a sense of immersion by combining two separate views, but it requires the brain to consume a large amount of computational power for image shaping.

The optical device of the eye solves three main problems: first, aiming content of the field of view so that it presents a greater distance, second, magnifying the content of the field of view for easy viewing by the user, and finally, the refraction of light delivered to the user's field of view.

The optical design system is divided into two structures or infrastructures for augmented reality and virtual reality: pupil forming and non-pupil forming. The observed effect of these two structures is shown in Fig. 3.8. The individual lenses are combined to form a non-pupil forming, designed to be projected directly onto the display through a magnifying glass. When rendering light, there is an obvious

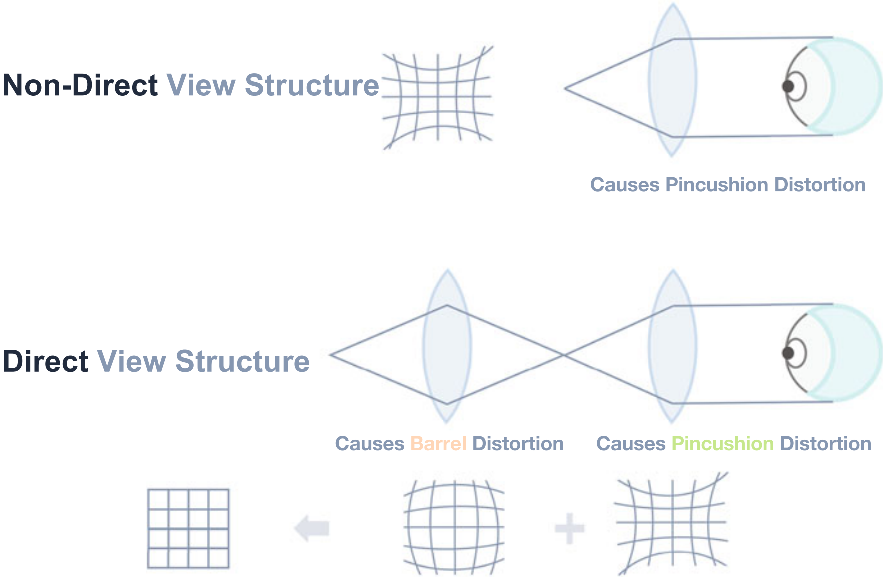


Fig. 3.8 Viewing effects in non-direct and direct view structures

drawback: pincushion distortion.[1] In a pupil forming, after a single lens produces cushion distortion, the second lens produces barrel distortion[2] which offsets the aberrations produced by the first lens, resulting in a more realistic and clear image. This design is widely used in devices that do not require a high degree of immersion, such as HoloLens and Google Glass.

When light encounters an obstacle or a small hole in the propagation process, the light deviates from the straight path and travels to the back of the obstacle. This phenomenon is called the diffraction of light. The finer the grating, the higher the resolution. The diffracted image is propagated on the optical path, and then the image is restored by the diffraction grating for high-quality image transmission.

The optical waveguide is a dielectric device that guides the propagation of light waves, also known as a dielectric optical waveguide. It achieves low transmission of light in the optical path through the principle of total light reflection. The optical waveguide application takes up little space and is conducive to the thinness of AR glasses. Still, the optical design is complex due to its complicated fabrication, high cost, and the different refractive indices of different colors of light that produce rainbow effects. A waveguide is a physical optical structure that allows light to curve into the human eye. It is used for internal reflection and control light entering and

[1] Pincushion distortion: the phenomenon of contraction to the center of the picture caused by the lens.

[2] Barrel distortion: the phenomenon of expansion around the screen caused by the lens.

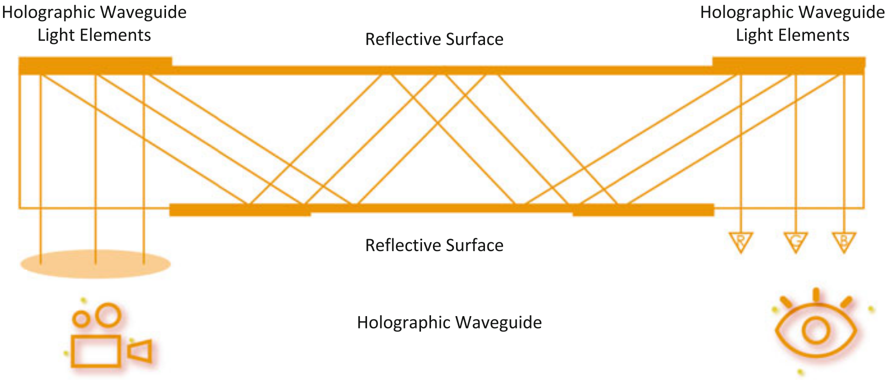


Fig. 3.9 The principle of operation of holographic waveguides

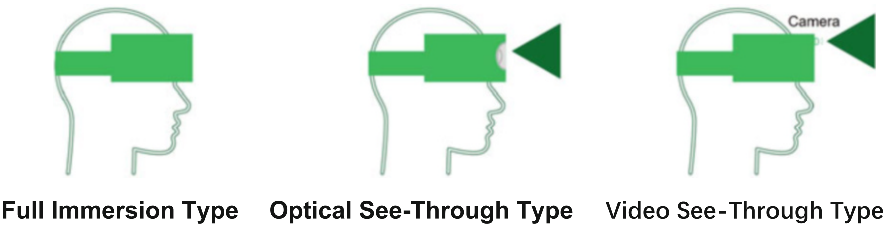


Fig. 3.10 Full immersion, optical see-through, and video see-through presentation diagrams

exiting. The industry has four waveguide structure designs: holographic waveguide, diffractive waveguide, polarized waveguide, and reflective waveguide. Holographic waveguides are a relatively simple type of waveguide used in optical elements. For example, for coupling and external coupling through a series of internal reflections, its principle of operation is shown in Fig. 3.9.

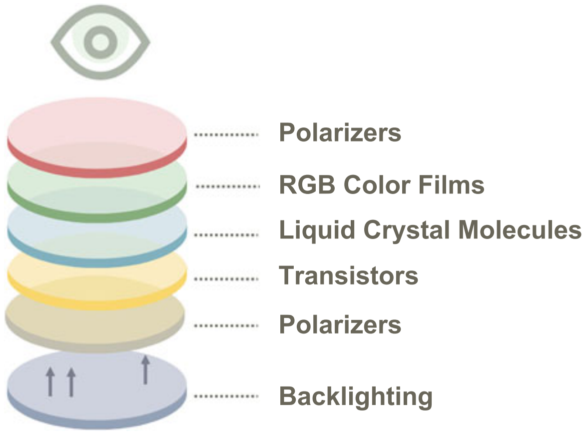
2. Image Display

There are three current display technologies: fully immersive, optical see-through, and video see-through. The presentation diagrams of these three types are shown in Fig. 3.10.

The fully immersive display is combined with sensors that completely block the user's view. In the "optical see-through glasses," the user can view reality directly through the optical components. HoloLens and Google Project Glass are recent examples of optical fluoroscopy through smart glasses. With video see-through smart glasses, users can view images captured by cameras and combine these camera views with computer-generated images to enhance user perception.

Image display technology is developing very rapidly. There are four major display technologies: liquid crystal display (LCD), light-emitting diode (LED), organic light-emitting diode (OLED), digital light processing (DLP), and LCoS.

Fig. 3.11 LCD structure diagram



LCoS is also an LCD and complementary metal-oxide-semiconductor (CMOS) integrated organic circuit combination of reflective new display technology.

a. Liquid Crystal Display

Liquid crystal display (LCD) is standard in HDTVs and consists of an array of cells containing liquid crystal molecules sandwiched between two polarizers. This unit is placed between a thin glass substrate with millions of transistors. A single RGB liquid crystal unit is called a sub-pixel, and three sub-pixels form a single pixel. For color LCDs, additional substrates containing red, green, and blue filters are placed on top of each substrate cell. The structure of an LCD is shown in Fig. 3.11.

Current flows through the glass material, and changing the current allows the LCD to adjust the passage of light to produce precise colors. If all sub-pixels are fully turned on, it will produce white light. Since the LCD unit does not emit light, a backlight is required to achieve that. The LCD unit can only vary the passage of light to produce the desired color and, subsequently, the image.

b. Light-Emitting Diodes

Organic light-emitting diode (OLED) is based on organic (carbon and hydrogen-bonded) materials, which emit light through carrier injection and compounding, and the light intensity is proportional to the injected current. Light-emitting diode (LED), under the action of an electric field, the anode-generated holes and cathode-generated electrons will move to the hole transport layer and electron transport layer injection, migrating to the light-emitting layer. When the two meet in the light-emitting layer, energy excitons are generated, which excite the light-emitting molecules and eventually produce visible light.

OLED can be made very thin compared to LCD due to its relatively simple structure, as it does not require an external backlight. Besides, the device consumes much less power, the screen image refreshes faster, has a higher contrast ratio, better color reproduction, and higher resolution. Most fully immersive head-mounted displays use this technology.

c. Digital Light Processing

Texas Instruments first developed the microdisplay digital light processing (DLP) chip. The display consists of approximately 2 million individually controlled micromirrors, each displaying a single pixel. The size of each micromirror is about 5.4 micrometers. RGB light is reflected on the micromirrors. Due to the nature of the micromirror, it can be redirected thousands of times in any direction in 1 s so that different shadows can be created on the retina depending on the color of the LEDs.

DLP microdisplays are one of the fastest display technologies available. The ultra-fast color refresh rate, low latency, low power consumption, and extremely high resolution make it an excellent choice for building head-mounted displays.

d. Liquid Crystal on Silicon

Liquid crystal on silicon (LCoS) is in between LCD and DLP displays. Unlike the transmissive technology of LCD, DLP is a reflective technology in which micromirrors reflect individual sub-pixels. As the light source passes through the reflective surface, it will pass through a series of sub-filters to modulate the light intensity and color. Similar to DLP displays, this technology is used in the Magic Leap One, which offers considerable flexibility when integrating with smaller devices due to its small size. With display technologies currently under development requiring extremely high resolution, flat-panel head-mounted displays may have become the history of AR devices.

Through the screen, users can observe the colorful virtual world. If display technology is the cornerstone, then data visualization is the booster that delivers multiple dimensions, levels, and spaces of data more simply to the user's view, greatly enriching the user experience.

3.2.2 Data Visualization

Data visualization transforms abstract data into graphics and images that are easier for humans to perceive. Through computer technology, data visualization transforms complex, abstract data into images that the human brain can more easily perceive by combining graphics, symbols, colors, etc. The data transformed into visual images can more intuitively convey the information it contains. The data information obtained by visualization is then used by users to form conclusions or decisions and disseminate and apply helpful information.

Data visualization focuses on the visual presentation and analysis of data. The visualization is closely related to the metaverse, and the process is shown in Fig. 3.12. The complete visualization process is mapping data space to visual space, from the raw data collected through data analysis to get the preliminary data, filtered to get the focus data (the more critical data after filtering). The focus data is converted into geometric data by mapping, and finally, the image data is obtained by rendering.

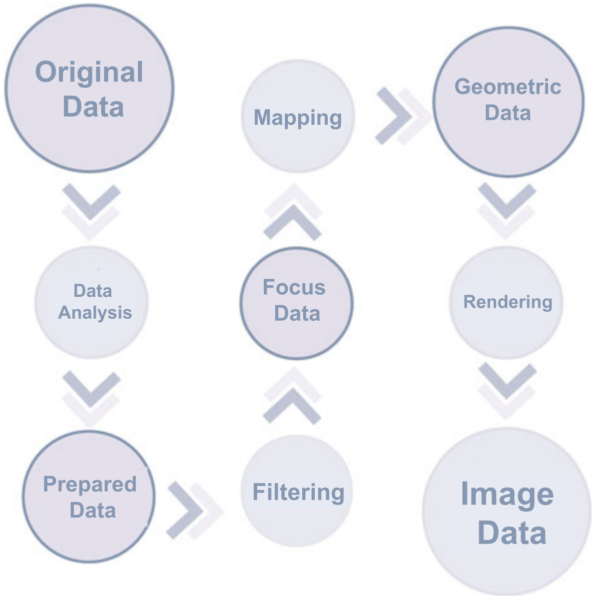


Fig. 3.12 Visualization process

The purpose of data visualization is to read three main aspects of information from the data:

- Patterns in the data: visualization allows effective presentation of important features of the data and discovers the objective patterns of the data
- Demonstrate relationships and correlations between different data
- Represents outliers in the data

Data visualization has three branches: scientific visualization, information visualization, and visual analytics.

Scientific Visualization

American computer scientist Bruce McCormack first introduced the concept and role of scientific visualization in his 1987 definition: "the use of computer graphics to create visual images that help people understand the intricate and often large-scale digital representations of the results of scientific and technical concepts."

Scientific visualization is oriented toward scientific and engineering data, such as 3D spatial measurements with spatial coordinates and geometric information, computer simulation data, and medical imaging data, focusing on the geometric, topological, and shape-based features to render the laws in the data. Scientific visualization focuses on the visualization of 3D phenomena in various systems such as architecture, meteorology, medicine, or biology. It is an interdisciplinary field of research and application that focuses on the realistic rendering of bodies, surfaces, and light sources and includes some dynamic (temporal) components. Scientific

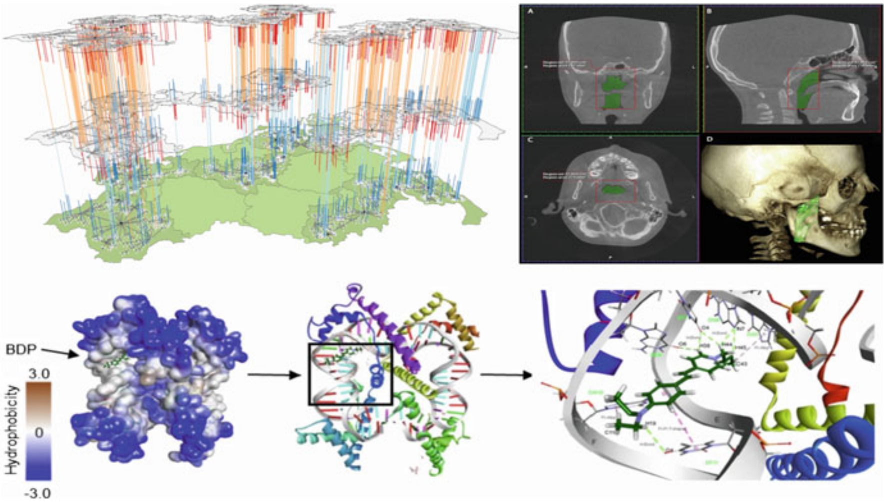


Fig. 3.13 Different examples of scientific visualization

visualization mainly uses computer graphics to convert textual information such as mathematical equations into objective visual images, thus helping the viewer quickly understand the situation and make better and faster judgments.

The 2007 ACM SIGGRAPH Symposium on Scientific Visualization identified visualization technology approaches involving 2D, 3D, and multidimensional visualization. Examples include color transformation, symbols for high-dimensional datasets, visualization of gas and liquid information, stereoscopic rendering, isoline and isoplanes, shading, particle tracking, animation, virtual environment techniques, and interactive steering. Further topics include interactive techniques, existing visualization systems and tools, esthetic issues in visualization, and related topics include mathematical methods, computer graphics, and general computer science.

Figure 3.13 illustrates several different examples of scientific visualization.

Data Visualization

Information visualization was introduced by Stuart K. Card, Jock D. Mackinlay, and George G. Robertson in 1989. It is mainly used to study the visual presentation of large-scale non-numerical information resources, in other words, to transform data information and knowledge into a visual form. Information visualization deals with unstructured, non-geometric abstract data, such as financial transactions, social networks, and textual data. Its central challenge is reducing the interference of visual obfuscation with information for large-scale high-dimensional complex data.

Ben Shneiderman, a professor at the University of Maryland, classifies data into seven categories: 1D, 2D, 3D, multidimensional, temporal, and network data. Information visualization methods can also be classified into the following seven categories according to different data: 1D, 2D, 3D, multidimensional, time series, hierarchical, and network information visualization. There is a difference between information visualization and scientific visualization. Scientific visualization is the visualization of spatial data fields, which focuses on how to display three-dimensional data fields in a realistic and fast manner. Information visualization, on the other hand, refers to the visualization of non-spatial data, which mainly uses images to display multidimensional non-spatial information, so that users can deepen their understanding of the meaning of information and, at the same time, use the intuitiveness of images to guide the retrieval process and speed up the process.

Information visualization can handle a wide range of types of Big Data, and this section classifies them into the following categories according to their characteristics: categorical data, time series data, spatial data, hierarchical data, and text data. Categorical data are variables with two or more categories, with no intrinsic ordering of the categories and no temporal trends, and are usually analyzed visually using a one-dimensional scalar approach; time series data refers to data with temporal attributes that change over time, which in turn contains temporal attribute data that need to be analyzed based on past temporal data and stream data that need to focus on changes in real-time; spatial data refers to data containing spatial dimensions, point data objects in spatial data are usually discrete points in geographic space with coordinates of longitude and latitude but without size dimensions, line data in spatial data usually refers to line segments or paths connecting two or more locations on a map, surface data (area data) in spatial data is generally described by the area of each geographic region to illustrate different object data corresponding to geographic locations; hierarchical data is a kind of data that focuses on expressing hierarchical relationships between individuals, abstracted into a tree structure, and defining relationships such as inclusion and subordination; and text data is a variety of textual data, such as item lists, personnel information, etc.

Figure 3.14 illustrates several different examples of information visualization.

Visual Analytics

Visual analytics is the science of analytical reasoning based on interactive visual interfaces, which integrates technologies such as graphics, data mining, and human–computer interaction to form a complementary and mutual enhancement of the advantages of human brain intelligence and machine intelligence. Data visualization can be static or interactive: static visualization provides users with a single view in front of them. Interactive data visualization large screens enable users to drill down into the data and extract and examine various perspectives of the same dataset, selecting the specific data points they wish to view in a visual format. A seamless combination of visual analytics and data visualization is required to derive the best insights from the data and get the most out of data analysis. Figure 3.15 illustrates a variety of different visual analytics examples.

Data visualization is mainly implemented with the help of programming. There are many standard programming libraries for visualization, such as D3.js, Recharts, Victory, React-vis, V Charts, Trading Vue.js, Chartkick, Flexmonster, Webdatarocks, ApexCharts, Chart.js Echarts, Frappe Charts, Nivo, Google Charts, amCharts, CanvasJS, Highcharts, and Zoomcharts, all of which are based on JavaScript. In addition, there are Python-based exploratory visualization libraries

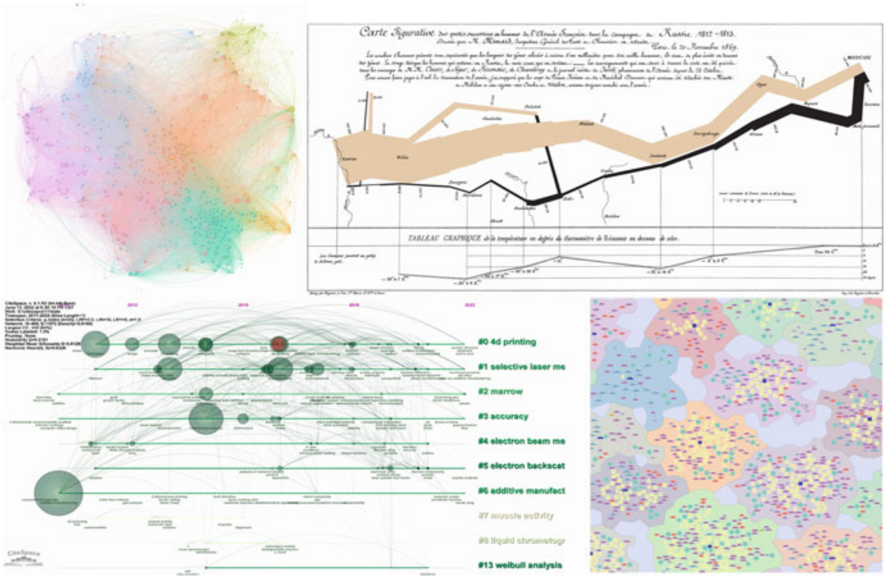


Fig. 3.14 Different examples of information visualization

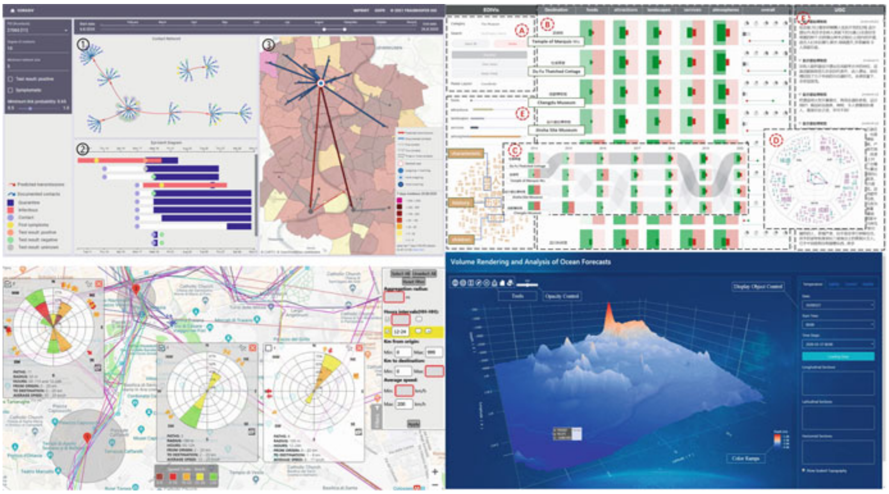


Fig. 3.15 Different examples of visual analytics cases

such as Matplotlib, Seaborn, Pyecharts, Missingno, etc. Some Python-based interactive visualization libraries also include Bokeh, HoloViews, Plotly, pygal, plotnine, Altair ggplot, and Gleam.

In addition, popular visualization software such as Tableau, Power BI, Dagoo, etc. makes visualization easy to do. For those with zero programming skills, you can also use graphing tools such as RAWGraphs, ChartBlocks, QlikView, Datawrapper, Visme, Grow, and iCharts, infographic tools such as Infogram and Visual.ly, map tools such as InstantAtlas, relational network graph tools such as Geiph, and mathematical graph tools such as Wolfram|Alpha. If you use visualization software as a developer, you can use programming libraries such as ECharts, D3.js, Plotly, Chart.js, Google Charts, Ember Charts, etc.

For more information on visualization, follow the journal IEEE Transactions on Visualization and Computer Graphics, the major conference IEEE VIS, the conference website for biology at www.biovis.net, and the website for visualization in economics at www.econvis.cn.

3.2.3 Computer Graphics

Computer graphics is the science of converting two- or three-dimensional graphics into the raster form of a computer display using mathematical algorithms. Simply speaking, computer graphics is the study of how to represent graphics in a computer and how to use computers to compute, process, and display graphics. Virtual reality is called the "next-generation Internet" and the "next-generation mobile computing platform." Computer graphics is the most important technology to realize virtual reality.

Unlike data visualization, computer graphics deals mainly with modeling, drawing, and rendering 3D objects. But there are also many connections between data visualization and graphics. Many sub-fields intersect, such as scientific visualization and graphics. This science technology is now widely used in computer-aided design and manufacturing (CAD/CAM), scientific computing visualization, computer games, and virtual reality. Computer graphics mainly includes modeling, rendering, animation, and human–computer interaction techniques. These four areas are described below.

1. Modeling

To represent a 3D object in a computer, it is first necessary to have its geometric model representation. Modeling is a technique for representing, controlling, analyzing, and outputting geometric entities by computer, describing a form based on geometric and topological information. As shown in Fig. 3.16, geometric modeling can reflect the static characteristics of a virtual object. The scope of geometric modeling is comprehensive, and several concepts in geometric modeling are introduced here, including triangle sets, mesh reconstruction, smoothing, and subdivision.

Set of Triangles The set of triangles is used as an expression for the geometry.

Mesh Reconstruction It generates a mesh to process the 3D coordinates of the discrete vertices obtained by the 3D scanner.

Smoothing It makes the triangle mesh look smoother by adding vertices.

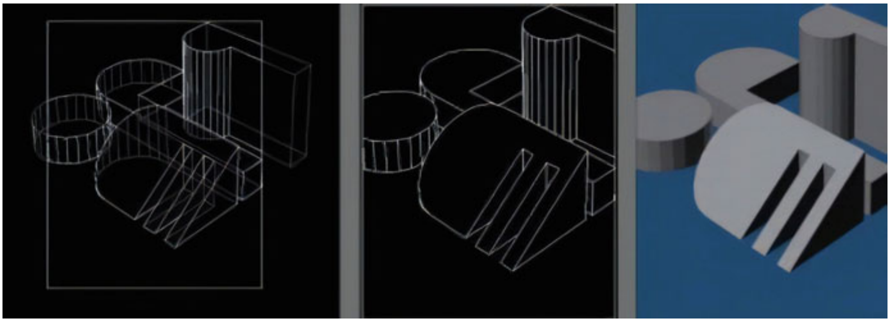


Fig. 3.16 Geometric modeling concept drawing

Subdivision It renders a smooth surface and makes the mesh show a hierarchical structure.

2. Rendering
Rendering is a technique for drawing 3D geometric models, which uses computer assistance to improve modeling realism. Current rendering techniques have been able to render various objects in a very realistic manner, including skin, trees, flowers, water, smoke, hair, etc. The main techniques are local illumination model, ray tracing, radiometric, global illumination model, Photo Mapping, BTF, BRDF, GPU-based rendering, etc.

Modeling and rendering are the two core technologies that enhance immersion and realism in the metaverse, and the current GPU-based imaging combines geometric modeling and rendering. The imaging process starts with geometric processing of the vertex data using geometric modeling techniques, then rasterization of the geometrically processed data using raster graphics techniques, and finally, exporting the image. As shown in Fig. 3.17, the modeling and rendering are coherent, which is the primary step of imaging.

The workflow of image rendering in computer graphics is shown in Fig. 3.18. The details are described below.

a. GPU Application Stage

- Prepare scene data (model, lighting, etc.).
- Clear out-of-field data.
- Set model rendering information (textures, materials, etc.).
- Output rendering elements (data such as points, lines, triangulated surfaces, etc.)

b. GPU Rendering Stage

Geometry Processing Manipulate rendered graphics elements, transform coordinates (e.g., transform vertex coordinates to screen coordinates), vertex information configuration (e.g., depth values, coloring for each vertex), and then output the coordinates, depth values, coloring, and other data for 2D vertices in screen space.

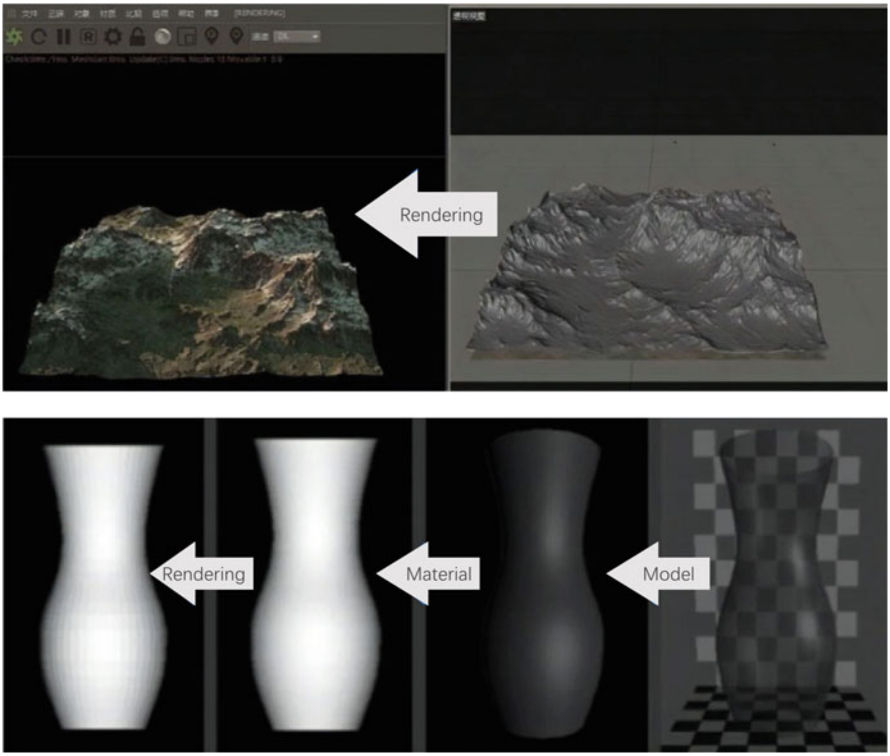


Fig. 3.17 Rendering comparison chart

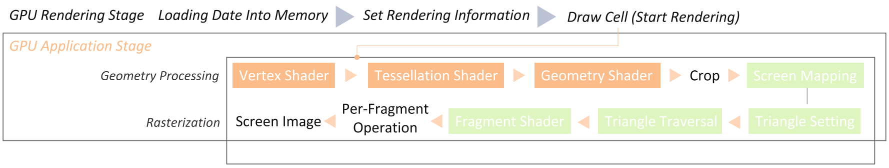


Fig. 3.18 Image rendering workflow diagram in computer graphics

Rasterization It converts vertex data to slice elements. Each element in the slice element corresponds to a pixel in the frame buffer. The essence of this is to turn geometric elements into two-dimensional images.

As shown in Fig. 3.18, the orange mark means programmable, unmarked means not programmable but configurable, and the green mark means not programmable and not configurable. The developer must compile vertex shaders, whereas the rest of the shaders are optional.

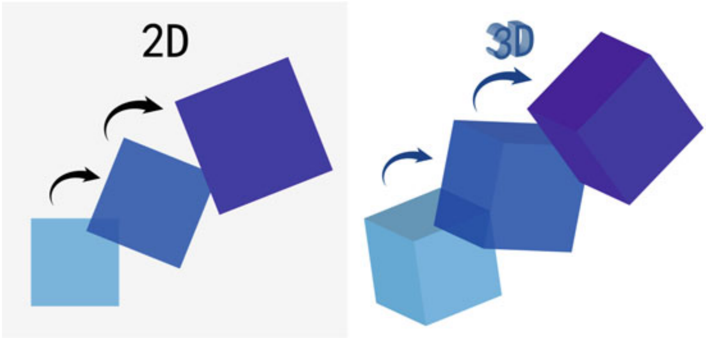


Fig. 3.19 Comparison of 2D and 3D

3. Animation

Animation is a technique that produces the effect of object movement by using continuous playback of still images. It mainly includes human animation, joint animation, physics simulation, motion animation, script animation, etc. It can also perform environment rendering.

In computer graphics, animation is divided into two categories: real-time animation and frame-by-frame animation. Real-time animation achieves the animation effect by modifying the pixel points on a frame. Still, the prerequisite is that the generation frequency of real-time animation and the frame refresh frequency of the device should finish matching. Frame-by-frame animation is similar to a movie projector, where each frame overlaps with the previous frame, each screen (frame) is a complete picture, and the coherent action effect is achieved by playing the screen quickly.

In terms of dimension, as shown in Fig. 3.19, animation can also be divided into two-dimensional animation and three-dimensional animation. Traditional two-dimensional animation requires the artist to draw one by one, and then the camera shoots one by one to form a coherent picture. After the emergence of computers, the production time of 2D animation can be shortened, and the process can be simplified. In the digital era, 3D animation can show the characteristics of objects in all aspects. Compared with 2D animation, it can reuse the material, reduce the cost, and use computer technology to simulate the movement of real objects and display them clearly in front of people's eyes. Commonly used animation tools include 3DMAX, AutoCAD, MAYA, OpenToonz, etc. Fig. 3.20 gives some demonstration examples.

In the metaverse, 3D animation greatly satisfies the consumer's imagination of the virtual world.

4. Human–Computer Interaction

Human–Computer Interaction (HCI) is a key technology in graphics and is also commonly used in data visualization. It mainly refers to technology transferring tasks and information between humans and computers through effective interaction.

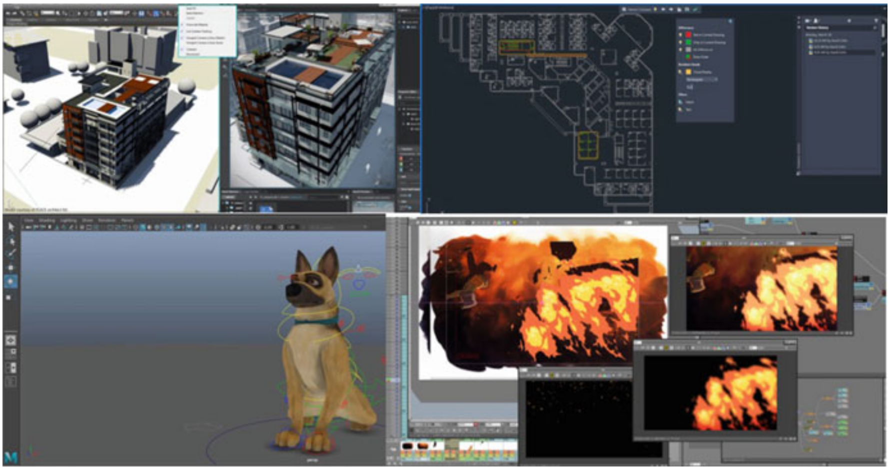


Fig. 3.20 Examples of common software used to create animations

The current mainstream interactive interface is a graphical user interface (GUI) based on WIMP (Window, Icon, Menu, Mouse). While new interaction ideas and fields such as language, 3D interaction technology, pose input, head tracking, visual tracking, stereoscopic display, sensory feedback, and natural language interface have been generated in recent years.

For example, Microsoft launched the XBOX360 physical peripheral Kinect in 2010, which does not require any controller. It only relies on the camera to capture the player's movement in 3D space and can import instant motion capture, image recognition, microphone input, voice recognition, social interaction, and other functions. Kinect is useful not only in the field of games but also in the field of medical rehabilitation to assist in physical rehabilitation training. In the area of space, NASA uses it to help space station personnel manipulate robotic arms. In the field of research, it has also significantly accelerated the development of hardware applications. A demonstration of Kinect is shown in Fig. 3.21.

There are also gestural interaction devices like Leap Motion and MYO wristbands that only listen to body parts (such as arms and legs). They can precisely recognize the movement of each joint of the hand and deftly grasp objects in virtual scenes. Unlike other somatosensory devices, these devices have a high degree of hand recognition due to their lightness and small size.

3.2.4 Other Supporting Technologies

In addition to virtual reality, augmented reality, data visualization, and computer graphics-related technologies, other technologies are needed to support superior

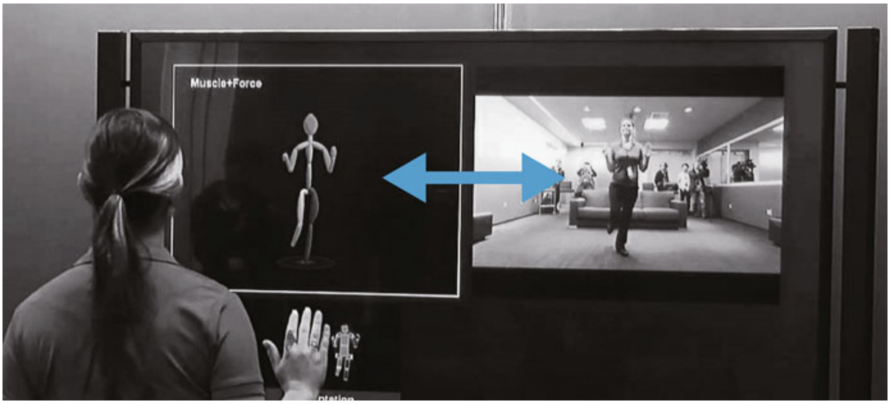


Fig. 3.21 Demonstration of Kinect

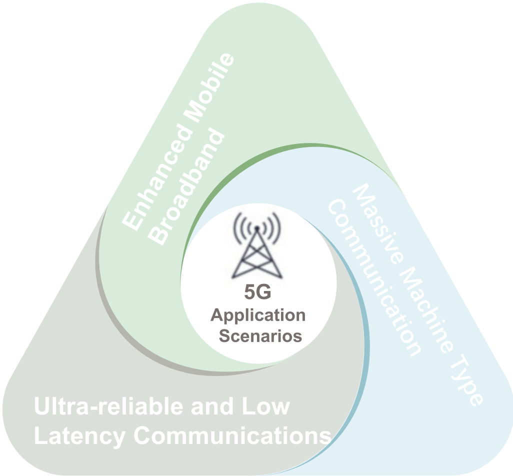


Fig. 3.22 Three major application scenarios for 5G

immersive interaction technology, such as communication technologies to achieve high synchronization, cloud computing technologies to solve the problem of a large number of users online simultaneously, and GPU for image rendering and algorithms as the infrastructure of the virtual world. Other supporting technologies related to immersive interaction technologies are described below.

Communication Technology: 5G

Immersive interaction technology requires high synchronization and low latency. Among them, 5G is the core technology to achieve high synchronization and low latency. The three major application scenarios of 5G are shown in Fig. 3.22. Enhanced Mobile Broadband (eMMB) for VR can improve the resolution and bit rate of the panoramic video, thus bringing a better viewing experience to users; ultra-

Reliable Low Latency Communication (uRLLC) can enhance the quality of image through cloud gaming technology solutions, thus reducing network latency in cloud gaming technology; and massive Machine Type of Communication (mMTC), i.e., massive machine type of communication, is mainly used in the Internet of Things, and the current Wi-Fi and Bluetooth are technologies that achieve connectivity in a small area. In the era of IoT, such connectivity technologies can no longer meet the demand. At the same time, 5G can achieve large-scale connectivity and provide technical support for the further development of IoT. Meanwhile, edge computing is often regarded as a key fundamental technology in the metaverse. By using an open platform close to the data source, the closest end of the service can be provided directly to the user, thus helping users replenish local computing power, improve processing efficiency, and minimize the risk of network latency and congestion.

According to test data from Open Signal, an independent third-party network testing organization, 4G LTE has an end-to-end latency of 98 ms, which can meet the interaction needs of scenarios such as video conferencing and online classrooms, but this is far from meeting the strict requirements of the metaverse for low latency. A major problem with VR devices is vertigo caused by transmission latency. 5G bandwidth and transmission rate increases can improve latency and reduce vertigo. According to Thales, 5G end-to-end latency can be controlled within 1 ms. A comparison of end-to-end latency with different communication technologies is shown in Fig. 3.23. In the metaverse, large amounts of data need to be transmitted quickly, which requires a robust communication infrastructure. However, the actual transmission rate of 5G may be challenging to reach its design level due to the limitation of the number of base stations. According to the vision of 6G network technology in Japan and Korea, 6G latency is expected to be reduced to one-tenth of

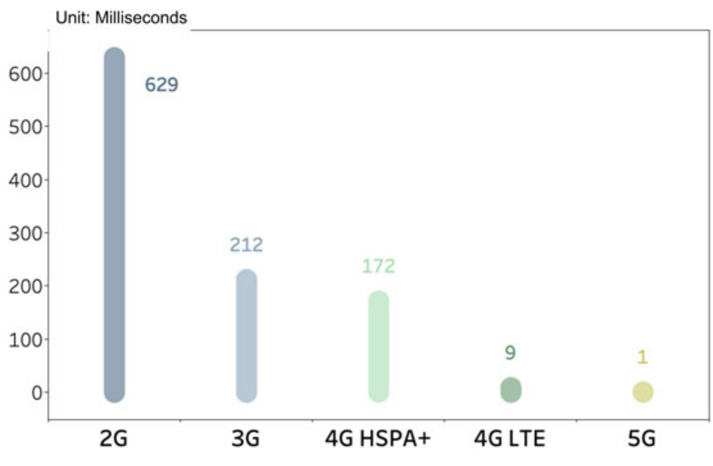


Fig. 3.23 Comparison of End-to-End Delay (milliseconds) with different communication technologies

5G, and the transmission rate is expected to be 50 times that of 5G. This technology is expected to achieve low latency in the metaverse truly.

Computing Technology: Cloud Computing
Cloud computing is a kind of distributed computing with powerful computing capacity, which is expected to solve the problem of a large number of users online at the same time. The metaverse needs to monitor data and perform massive computations in real-time so that users can log in with any device and be immersed anywhere, anytime. It is difficult for a single or a few servers to support the massive computation in the metaverse. With the powerful computing power of the cloud, cloud games can move processes such as rendering to the cloud. Compared with games running on terminals, cloud games significantly reduce the game's dependence on terminal device performance, and its fast gameplay meets the characteristics of a metaverse that can be accessed anytime and anywhere. VR devices require high-performance CPUs, storage, and transport components to support computing, resulting in heavier devices that are difficult for users to wear for long periods. With the clouding of VR device arithmetic, VR terminal equipment is expected to achieve lighter weight, lower costs, and smoother graphics.

Image Rendering: Arithmetic
For virtual world simulation, GPU is the leading computing power base hardware, and the computing power of GPU is essential for a realistic virtual experience. As of November 2021, NVIDIA, AMD, and Intel are the only companies capable of mass-producing GPUs in the consumer PC space. Integrated GPUs dominate Intel, AMD has both integrated and discrete GPUs, and discrete GPUs dominate NVIDIA. The sophisticated hardware architecture of GPUs results from a long evolution of technology. It enables GPUs to support many advanced graphics processing steps, including vertex processing, rasterization, texture mapping, and more.

Infrastructure: Algorithms
The engine defines the basic rules and presentation in the virtual world through algorithms. These rules include "lighting effects," "animation system," "physics system," and so on. The role of the engine is to reduce the duplication of development and lower the development threshold. Typically, machines perform physical model calculations, AI calculations, image rendering, and sound and animation system rendering. Unity and Unreal are some of the famous engine platforms on the market today.

3.3 The Application of Immersive Interaction Technology

The metaverse is inseparable from virtual reality, visualization, and graphics technology. Bringing high immersion to users is one of the core functions of the metaverse, and the support for this technology lies in immersive interaction technology. XR (VR, AR, and MR) and other devices can present realistic artistic special effects on the one hand and allow users to enter the virtual world as avatars and realize various interactions such as gestures on the other, so these devices are the entrance to the metaverse. Hardware and operating system as the entrance to the metaverse directly determine the scale of users. The underlying architecture determines the stability of the metaverse operation, and the grounded applications demonstrate the charm and prospect of the metaverse, as well as the motivation and purpose of studying these technologies. This section focuses on the grounded applications of various immersive interaction technologies.

3.3.1 Digital Twins

The concept of the "digital twin" first appeared in 2003 in a course on product lifecycle management taught by Professor Grieves at the University of Michigan. The interactive mapping of digital models constructed in virtual space to physical entities faithfully describes the trajectory of physical entities throughout their lifecycle. In 2010, digital twin was formally introduced in a NASA technical report and defined as "a system or vehicle simulation process that integrates multiple physical quantities, scales, and probabilities."

By reviewing numerous pieces of literature, we conclude that the physical object will be transformed into data in the digital twin. The data and principles will be modeled, then the mechanism model and data-driven model in the model will realize self-learning and dynamic adjustment, and finally, the model will be loaded into the software, and the software will recognize the functions of describing, diagnosing, predicting, and deciding on the physical object. The whole process is shown in Fig. 3.24.

A digital twin is a digital dynamic twin that creates things from the real world in virtual space. With the help of sensors, the operating state of the body and data

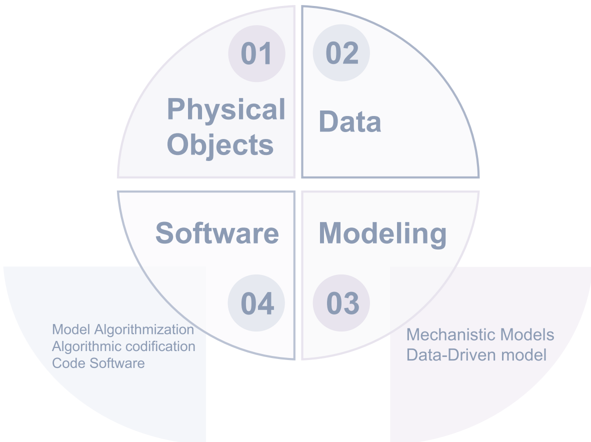


Fig. 3.24 Digital twin definition

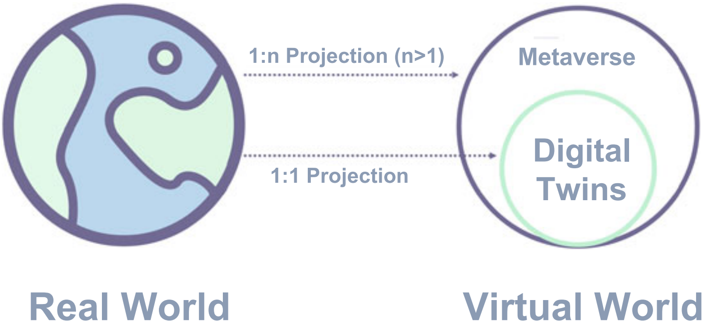


Fig. 3.25 Digital twins and metaverse: cloned universes and multiverses

from the external environment can be mapped to the digital twin in real-time. The essence is to create a digital version of a "clone," also known as a "digital twin." The digital twin realizes the feedback from the real physical system to the digital model in virtual space. Various simulations, analysis, data accumulation, exploration, and even artificial intelligence applications based on the digital model apply to the real physical system. The technology was initially used in industrial manufacturing, where the metaverse required digital twins to build realistic environments with rich detail and create immersive clinical experiences.

The digital twin can replicate the physical elements of the real world, and its end product is a "clone universe" that mirrors the real world. The metaverse is a copy and modification of the real world based on the logic of reality or illusion (e.g., surrealism, science fiction, etc.). It presents the "multiverses" in an open mode. The relationship between the digital twin and the metaverse is shown in Fig. 3.25.

Characteristics of the Digital Twin

There are many characteristics of the digital twin, which are not uniformly stated in various literature. The characteristics of the digital twin can be summarized as interoperability, real-time, scalability, fidelity, and closed loop, as shown in Fig. 3.26.

Interoperability The digital twin's physical objects and digital spaces can be mapped, dynamically interacted, and connected in both directions. Thus, the digital twin can map physical entities to various digital models and transform and fuse between different digital models.

Real-Time Because the digital twin is going to reproduce physical entities that change with the timeline, the data needs to be managed so that computers can recognize and process, namely, digitized.

Scalability Digital twin technology can integrate, add, and replace digital models and extend model content.

Fidelity The digital twin requires virtual objects to maintain a high degree of simulation not only in terms of solid geometry but also in terms of state, phase,

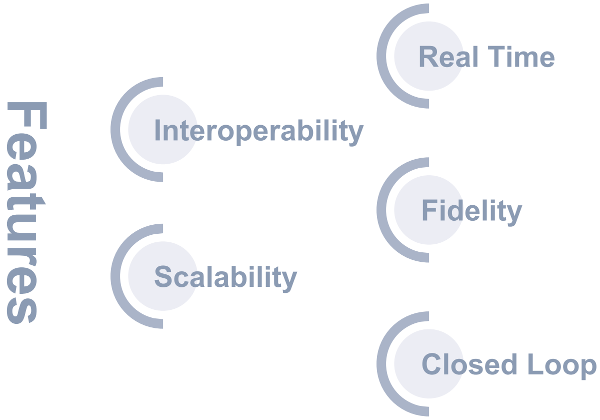


Fig. 3.26 Schematic diagram of the characteristics of the digital twin

and temporal state, making every effort to ensure the similarity between the digital virtual model and the physical entity.

Closed Loop The digital virtual body in the digital twin is used to describe the visual model and internal mechanisms of the physical entity, thus monitoring the state data of the physical entity, performing analytical reasoning, optimizing process parameters and operational parameters, and implementing decision-making functions, in other words, using a closed-loop system for both the virtual body and the physical entity.

Application Scenarios for Digital Twins

Currently, the application scenario of the digital twin is mainly for B-side users. In recent years, with emerging technologies such as artificial intelligence, the digital twin has been widely used in aerospace, power, shipping, agriculture, health, and medical fields. Especially, in the areas of smart manufacturing and smart cities, a digital twin is considered to be an effective means to integrate manufacturing information/urban information with the physical world, especially in the areas of smart manufacturing and smart cities. From 2017 to 2019, the digital twin was selected as one of Gartner's Top 10 Strategic Technology Trends for three consecutive years.

Currently, the main application areas of the digital twin include digital design, virtual factories, equipment maintenance, smart cities, smart healthcare, etc. (as shown in Fig. 3.27).

Digital Design The digital twin technology is used to create a digital twin of the product design and perform system simulation in the virtual space to achieve feedback design, iterative innovation, and continuous optimization. Currently, digital design practices in prototype design, process design, engineering design, and digital prototyping have been commonly carried out in automotive, marine, aerospace, and precision equipment manufacturing.

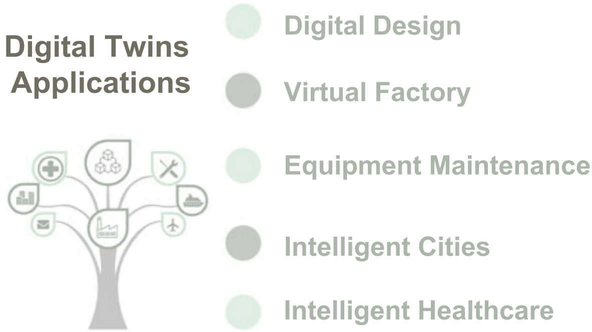


Fig. 3.27 Digital twin application areas

Virtual Factory Virtual factory refers to the digital virtual workshop and digital factory based on the combination of digital twin technology and MES. It can realize the dynamic data interaction between physical entities and digital virtual entities and forecast production in real-time according to the changes in the virtual space.

Equipment Maintenance Develop and design the devices digital twin and interact with the physical entity synchronously to achieve digital management of the device lifecycle.

Smart City By building a digital twin of the city, we simulate the interaction of weather, infrastructure, population, land, industrial transportation, and other elements in the digital world in a combination of quantitative and qualitative forms and draw a “city portrait” to help decision-makers improve urban planning in the physical world.

Smart Healthcare The digital twin is combined with medical services to achieve dynamic monitoring, simulation, and modeling of the human body’s operating mechanism and medical devices, accelerate the transformation of scientific research innovation into clinical practice, improve the efficiency of medical diagnosis, and optimize the control and supervision of medical device quality.

3.3.2 Other Applications

Immersive interaction technology is currently applied more often. In addition to the digital twin, several typical applications are introduced here, such as holographic projection sandbox, immersive interactive experience room, holographic transparent screen, and holographic live broadcast, as shown in Fig. 3.28.

Holographic Projection Sandtable
Holographic projection sandtables are commonly available as portable holographic sandtables and holographic interactive tables.

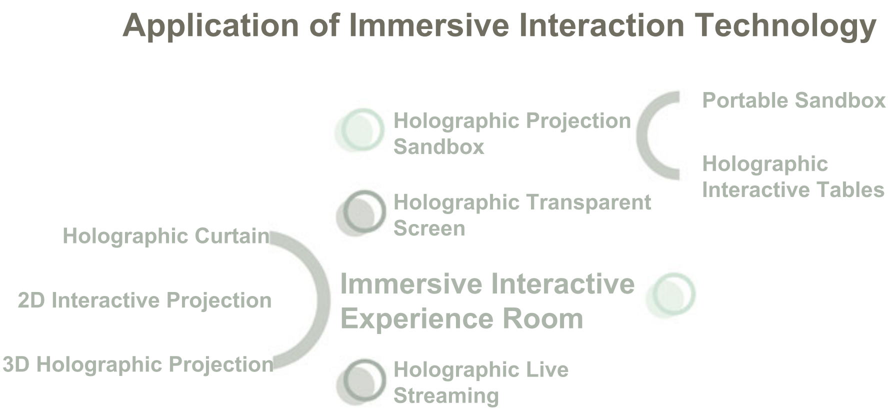


Fig. 3.28 Application of immersive interaction technology

Portable holographic sandtables can realize desktop floating 3D sandbox image and support Aerial gesture interactive operation and a variety of three-dimensional format file import and editing. Users can touch the 3D virtual image in the sky. It has a stronger sense of "real" experience than other traditional holographic products and supports external display. Users only need to wear lightweight holographic 3D glasses to synchronize the desktop image content, as shown in Fig. 3.29.

The holographic interactive table uses 4K HD projection, and the projection equipment is often mounted on the ceiling. It projects 3D images from top to bottom without blocking the rear. It can be paired with a large screen to launch and interact simultaneously to display 3D view images from different locations accurately. Other features are the same as the portable holographic sandbox. This device is more suitable for fixed venue applications, as shown in Fig. 3.30.

Immersive Interactive Experience Room

The immersive interactive experience room includes a holographic screen, a 2D interactive projection experience room, and a 3D holographic projection experience room. The holographic screen uses wall 3D projection and spatial tracking and positioning technology. Users can wear holographic 3D glasses to move freely in space, watch 3D images jumping out of the wall from different positions and angles, and combine with gestures, handles, and other interactive functions for a virtual interactive experience, as shown in Fig. 3.31.

The 2D interactive projection experience room uses a different approach. Interactive projection uses a capture device (sensor) to capture the target image (such as a participant) and then is analyzed by an image analysis system to generate the movement of the captured object. This motion data is combined with a real-time image interaction system to create a tightly integrated interactive effect between the participant and the screen. The 2D interactive projection experience room is a surrounding immersive first-person simulation experience space created by

Fig. 3.29 Portable holographic sandtable

seamlessly stitching together multiple projection screens, which support human–computer interaction such as handles and gestures, as shown in Fig. 3.32.

3D holographic projection experience room uses holographic projection technology, bringing a more robust immersion than a 2D interactive projection experience room. Holographic projection technology is a virtual imaging technology that uses the principles of interference and diffraction to record and reproduce the real three-dimensional image of an object. It uses the interference principle to record the light wave information of the object and then uses the diffraction principle to produce the light wave information of the object to get a three-dimensional image almost identical to the original object. The 3D holographic projection experience room can provide a large immersive holographic 3D interactive experience by stitching together four sides of 3D images, thus realizing live 3D stereoscopic images and enhancing realistic live immersive experience, as shown in Fig. 3.33.

Holographic Transparent Screen

The holographic transparent screen realizes aerial naked-eye 3D image playback, creating a display environment that combines virtual and reality. Various virtual interaction functions such as gestures, voice, and touch screens can be added to enhance the display and interaction experience. The unique optical material on the transparent screen can reflect the image of the projection device and present the projected 3D image on the transparent display. The area where the image is not

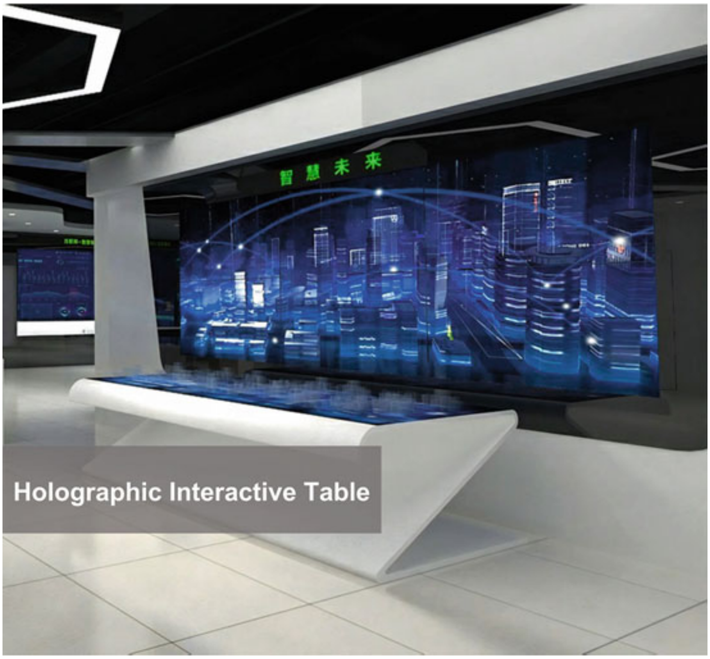


Fig. 3.30 Holographic interactive table

Fig. 3.31 Holographic screen concept diagram

Fig. 3.32 Immersive interactive projection experience room (2D immersion)

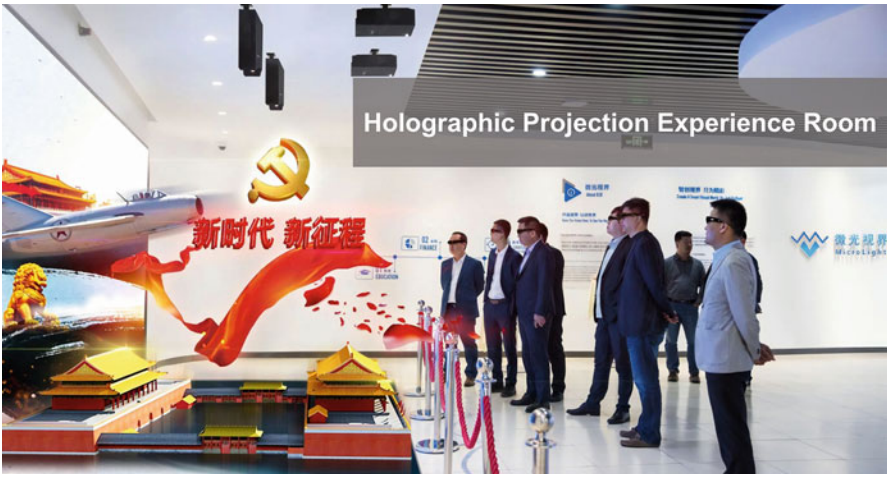


Fig. 3.33 3D holographic projection experience room

Fig. 3.34 Museum holographic transparent screen

displayed is the transparent glass effect, which can see through the real environment behind it, thus showing the naked-eye 3D, virtual, and real three-dimensional image effect. It can also meet the demand for multi-person naked-eye 3D viewing and interaction, as shown in Fig. 3.34.

Holographic Live

The holographic live broadcast is a new way and development direction of the live broadcast. Through holographic projection technology, viewers can see clear, three-dimensional, realistic live images and feel the "immersive" live interactive experience. It adopts broadcast-grade 4K ultra-high-definition production and broadcasting system, easy and intelligent operation, green screen system, real-time GPU keying function, holographic transparent screen, and real-time processing and transmission of the holographic human image to the display site. As shown in Fig. 3.35, it also provides a virtual scene editor so that users can create their virtual scene backgrounds. Combined with the low latency of 5G, it realizes a smoother holographic live interactive experience.

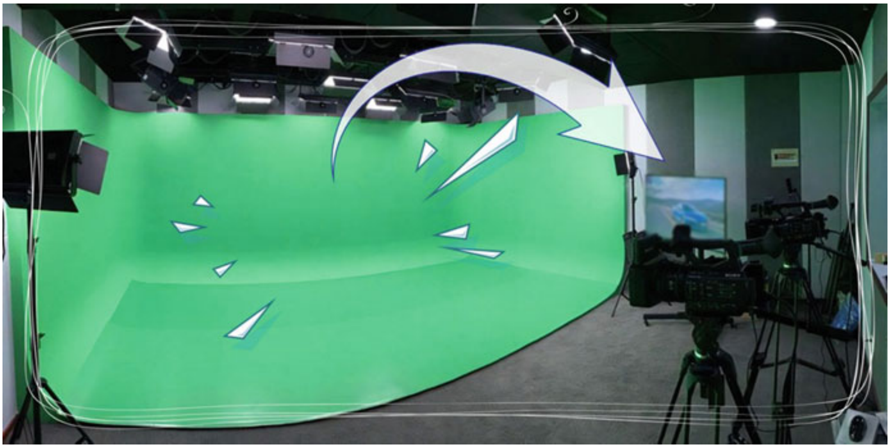


Fig. 3.35 Holographic live

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