Developments of Sensing Technology and its Applications in Virtual Reality

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Abstract. Virtual Reality is one of the hot research directions recent years, as a 5G rea oriented technology and a new way of displays, virtual reality has shown us its huge potential in industries, especially in entertainment, medical science and education. Sensing technology is widely used on VR in many aspects such as the HMD displaying system, position and motion tracking module and the input devices like VR controllers, while most overview papers pay attention to the concepts and applications, though some of them illustrated all the technologies roughly. This overview article has focused on sensing technology in VR, introducing the techniques in some commercially successful VR devices, comparing and summarized some of the latest research based on them, with which it may help users and researchers understand VR devices better and choose the appropriate devices while using. In the end, the paper summarizes the whole paper and prospects the future development direction.

Keywords: Virtual Reality; Sensor; Head-Mounted Display; Position Tracking; Controller.

1. Introduction

Virtual reality (VR), a new concept in the middle 20th century that first presented by Ivan Sutherland, was called “The ultimate display” due to its exquisite display ability. Since then, people began understanding this “window of watching the virtual world”, researching it in lots of aspects. Nowadays, characteristics about action responding, real-time 3D graphics and immersive sensing are initial to the virtual reality system, making up an immersive experience for users [1]. Sensing technologies are widely used in responding to user actions, which use unique devices like head-mounted display, position tracking sensors and controllers.

As the computer science and the Internet develop rapidly, information technologies’ iteration obeys Moore’s law that every 1.5 years a new generation of them occurs. Virtual reality, as the new technology facing to the next generation of the Internet and communication technologies, contains a series of technologies from several aspects [2]. Sensing technology is one of the most significant technologies which has lots of usages in virtual reality, like the head-mounted display (also known as HMD), optical tracking for users’ location and sensor controllers, etc. However, it is still kind of sparse about the paper reviews for VR sensing technology, most of which heading on one concrete technology that could not represent the newest developments of all of them. This article summarized the VR sensing technology field, especially focusing on HMD, position tracking and the controllers’ developments. Through the analysis of these aspects, the latest developments of VR sensing technology can be fairly summarized.

2. Head-Mounted Display (HMD)

A head-mounted display is a virtual reality headset that closes people's vision and hearing senses, which makes up to the immersion that users feel like being in an unrealistic world. Users need to wear a headset, which has two screens simulating people’s eyes and show the virtual scenes, as well as three space tracking locators allow users make some movements like walking straight, turning left and right, or even jumping and squatting [3]. These locators collect the real-time position changes of the headset the user is wearing, sending the data to the computer or cellphone that controls the device, and it will show the changes of virtual scenes that the user can have seen after calculating the data of position changes and applying it into switching the scenes shown in HMD.

2.1 Technology used in HMD

An HMD system contains display systems and measurement devices (figure 1). As the HMD system needs to be mounted in front of the users' eyes, the development of an image presentation method that matches heads' movements and the devices of recording eye movement are also under development [4]. These new technologies are also being applied in more and more new fields.

Fig 1. Oculus Rift S Head-mounted display

There are two display systems in HMD, one for the left eye and the other for the right, which provides great performance in displaying stereoscopic images. The displaying principles of HMD are totally different from CRT, which is widely used on the screens of televisions, computers and cellphones, that also cause problems in the applications [5]. In HMD's display systems, users' visual load may be increased due to the interference the accommodation distance makes on the convergence distance in human eyes.

2.2 Applications and Analysis

Display systems exhibit virtual scenes to users' eyes. Mostly the display systems in HMDs use LCD screens. Twisted nematic screens are the most common LCD monitors now, which response very fast (usually less than 1ms) and have high frame rate for more than 90 frames per second, while its color representation capability and viewing angles are unsatisfactory.

Twisted nematic screens are used in Meta Quest 2, which changed it from the OLED screen. Another kind of LCD screen is in-plane switching (IPS) screen. IPS screen has a better quality in pictures, with better color representation capability and viewing angles, but it has low refresh rate, as it costs a lot to get a high refresh rate IPS screen, so it is not widely used in any HMDs [5-7].

Organic light-emitting diodes (OLEDs) are a new kind of LEDs which mostly use the electroluminescence including fluorescence and phosphorescence. A breakthrough which was achieved by Tang's team that reported efficient and low-voltage ones from p-n heterostructure devices using thin films of vapor-deposited organic materials. This research led the OLED to the technology that face the future on screens. Flat-panel display also showed its high performance in the applications, like its self-emitting property, high luminous efficiency and flexibility, etc [4].

Two kinds of OLEDs are widely used (PMOLED and AMOLED). Although PMOLEDs have lower production cost comparing with AMOLEDs, their lifetime is not ideal for VR devices, as well as AMOLEDS show amazing black color performance and very high refresh rate that make them perfect for VR devices. Both HTC Vive and Oculus Rift [8] have used AMOLEDs for their HMDs.

Comparing to OLEDs, the advantages of LCD screens in HMDs include standard RGB and delicate display, a significant reduction of screen door effect in OLED displays, higher brightness, relatively lower power consumption and cost. However, a lower screen response time, obvious screen smear, lower contrast ratio, disadvantages in color gamut and color uniformity of LCDs perform not great.

Technologies of different HMDs are shown in Table 1. Competitions between LCD and OLED displays have not yet ended with a winner now, as the mainstream VR display manufacturers are still exploring a better solution with their own techniques, but the properties can be tested with these products. HTC Vive Pro and Oculus Rift CV1, which use OLED displays, have higher refresh rates and field of view than others that use LCD displays, while LCD displays often bring better resolutions no matter it is for per eye or a combination.

Table 1. Different HMD properties

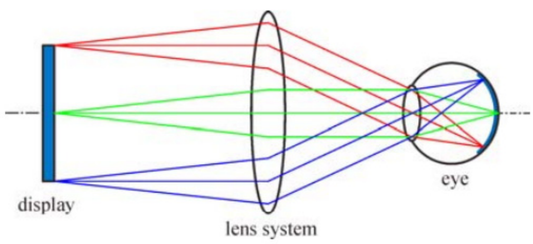
Products	Screen	Resolution	Refresh Rate	Field of View
HTC Vive Pro	Dual AMOLED 3.5" diagonal	1440 x 1600 pixels per eye (2880 x 1600 pixels combined)	90 Hz	110 degrees
HTC Vive Pro 2	Dual RGB low persistence LCD	2448 x 2448 pixels per eye (4896 x 2448 pixels combined)	90/120 Hz	120 degrees
Meta Quest 2	Fast-Switch LCD Display	1920 x 1832 Resolution Per Eye	60/72/90 Hz	90 degrees
Oculus Rift CV1	OLED	1080 x 1200 Resolution Per Eye	90Hz	94 degrees
Oculus Rift S	LCD	1440 x 1280 Resolution Per Eye	80Hz	More than 100 degrees
Meta Quest 2 Pro	2.48" mini-LED displays	2,160 × 2,160 resolution per-eye	-	-

Unfortunately, Oculus Rift CV1 and Oculus rift S are no longer available now, replacing with Meta Quest 2 Pro that will be released in the second half of 2022, trying mini-LED displays with 2160 x 2160 resolution per eye designed to bring such panels closer to OLED performances [5].

Meanwhile, retinal projection technology is another way to show the images to users without a screen, just by emitting image pixels of light source or laser source to human retina. Retinal projection was developed from retinal scanning technology which the medical imaging area always use for getting the retina's fundus or a near-eye display [6]. Fig. 2 shows different principles of views of HMDs and retinal projection display (RPD) by Maxwellian.

Retina projection technology is a promising technology for virtual reality, which can solve many of the problems plaguing current all-in-one display technology. It is more promising than other display methods in terms of color, latency, image detail, etc. However, as a consumer-grade technology, it's still fairly expensive and requires all sorts of improvements and cost reductions to really hit the mainstream market. Avegant tried to embed retina projection on their HMD product called Avegant Glyph, after which people show more interest on its augmented reality applications.

2.3 Advanced Research in HMD



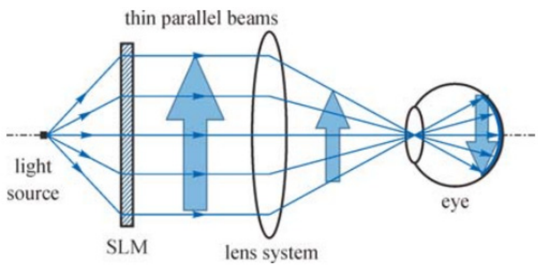


Fig 2. Normal HMD viewing and RPD principle

Research among technologies in HMD develops, aiming at solving the problems that HMD has, like the field of view is too small, long-time wearing HMD increasing the visual load, and so on. Takashi Shibata conducted some experiments to investigate the visual load as people use HMDs watching stereoscopic images [2]. Kizashi Nakano proposes a new downward field of view based on HTC Vive, giving a 60 degrees' improvement to its vertical FoV[3]. Table 2 illustrates the FoVs of HTC Vive and Nakano's prototype.

Table 2. FoVs measured an equidistant projection fisheye camera

FoV	Horizontal	Vertical (upper + gap + lower)
Original HTC Vive	~70 [deg]	~70 (40 + 0 + 30) [deg]
Nakano's prototype	~70 [deg]	~130 (40 + 10 + 80) [deg]
Difference	±0 [deg]	+60 (0 + 10 + 50) [deg]

As it was mentioned before, the screen door Effect (SDE) has been one of the common visual artifacts in modern VR headsets, which is also a common complaint from users. Jilian Nguyen and his team from The University of Arizona and Facebook Reality Labs examined a mechanical pixel shifting method to limit SDE and, as a result, by the two different ways of pixel traces that called Non-Redundancy and Redundancy shown in Fig 3, they found it not only reduced SDE but also seemed to sharpen the images. [7]

Some research may aim at embedding new functions and hardware devices to HMDs to accomplish a convenient application of their purposes, such as sensing users' facial performances. Hao Li and his colleagues from University of Southern California designed a novel HMD for real-time 3D facial performance-driven animation [10]. With a standard HMD (the Oculus Rift DK 2) and additional sensing hardware (an RGBD camera), the new system can accurately record and analyze users' facial expressions and divide them into different groups as they are using the system.

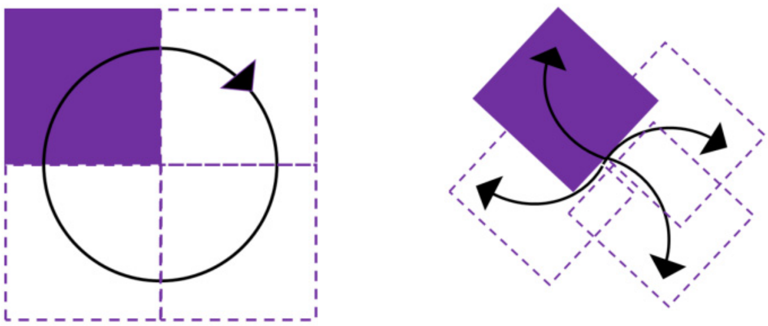


Fig 3. Non-Redundancy pixel trace (left) and Redundancy pixel trace (right)

3. Position Tracking

3.1 Why VR uses Position Tracking

Virtual reality has a feature that makes it unique: immersion. To build a more immersive and interactive VR experience, these VR devices are designed to show a ubiquitous virtual world to people, as the HMD occupies all the vision of people. At the time people begin to use it, they get a virtual location in the virtual world, which also allow them to move and make some actions.

Meanwhile, VR devices that support somatosensory interaction can greatly improve the sense of immersion, as well as the interactions among users and virtual scenes are fundamental during the VR experience. Position tracking technology is fundamental in the somatosensory interaction, that various categories and products can be subdivided, such as somatosensory seats, treadmills, somatosensory clothes, spatial positioning technology, motion capture technology, etc.

Position tracking technology depends on HMDs and controllers in nowadays commercial VR devices, and it is interesting that every device from different companies have different tracking solutions combining with their own devices, as they have significant differences on performances.

3.2 Techniques and Commercial Products

3.2.1 Lighthouse Positioning Technology

Lighthouse positioning technology relies on lasers and photosensitive sensors to determine the position of moving objects. By installing the sensors on the diagonal of space, the system can emit laser beams 6 times per second. two scanning modules are also contained for getting space coordinates which also take turns to emit lasers to scan and locate the space.

Lighthouse positioning is widely used by the HTC Vive, with up to 70 photosensitive sensors installed on the HTC Vive's head-mounted display and two handles. It calculates the time of receiving the laser to obtain the exact position of the sensor position relative to the laser transmitter. A light-sensitive sensor to derive the position and orientation of the headset/handle.

3.2.2 Infrared Optical Positioning Technology

The principle of infrared optical positioning technology is covering the working area by installing IR-emitting cameras. The surface to be positioned is installed with infrared reflective points. The infrared light is reflected by some points, working with multiple cameras and then calculating through subsequent programs, can obtain the spatial coordinates of the positioned object. Oculus Rift adopts this technology.

Actually, there is not infrared reflectors on the HMD and Touch devices of the Oculus Rift but infrared lights. Then two cameras with infrared light filters embedded capture the infrared light from the HMD and Touch, then get their space coordinates by calculating on the computer.

In addition, the Oculus Rift also has a built-in nine-axis sensor. Its function is to use the nine-axis sensor to calculate the spatial position information of the device when the infrared optical positioning is blocked or blurred, so as to obtain higher-precision positioning.

3.2.3 Visible Light Positioning Technology

Visible light positioning technology is somewhat like that of infrared optical positioning technology. It also uses a camera for getting the position of the tracked object, while it no longer uses infrared light but directly uses visible light, which can emit different colors when installed on different objects being tracked. The camera captures these colored light spots to differentiate the isolated objects and their position information.

PlayStation VR (PSVR) from Sony showed in Fig 4 uses this kind of technology for their tracking missions. With the blue light from its HMD and sky blue or pink lights from its left and right handles, the computer can get the space coordinates of the light ball after the binocular cameras obtaining light information.

Fig 4. PSVR devices

3.3 Comparison

The key indicators when position tracking technologies are compared mostly contain 3 aspects: the working area, tracking accuracy and jitter. One more thing that consumers always concern about is the price of devices. Table 3 demonstrates the recommended working area and the prices of the VR devices mentioned in 3.2. Despite the release time of these devices, the recommended working area of a VR device is proportional to its price. The most improvement of the recommended working area is made by HTC Vive Pro, which is a new generation of HTC Vive, comparing to its elder edition with a 4 times larger area, pricing as more than $100 USD as the elder one.

Table 3. Recommended working areas and prices of different VR devices

VR Device	Recommended working area	Price
HTC Vive	6.25 m^2	$499 USD
Oculus Rift	2.75 m^2	$300 USD
PlayStation VR	5.7 m^2	$399 USD
HTC Vive Pro	25 m^2	$599 USD

Meanwhile, Adria´ n Borrego's team conducted an experiment examining the differences of the two HMDs from Oculus and HTC in the recommended and actual working area by their measurement, together with their accuracy and jitter data analysis. They first marked a 10x10 grid with 50x50 cm squares and setting the experimental floor of 25m^2, then placing the Oculus camera and HTC Vive base sections respectively, based on their recommended maximum distance. HMDs for the tracking camera or base station were set at 50Hz and registered for 5 seconds. As the result shown in Fig 5 and Table 4, both of them had a larger working area in the actual use than it was recommended, as well as HTC Vive supported far more area than Oculus Rift. HTC Vive's large working area also made it not as accurate as the other, while the jitter of both did not show differences with the areas considered [8].

Table 4. Comparison of the accuracy

	On the floor (0m)			Sitting Position (1.3m)			Standing Position (1.7m)	
	Oculus Rift	HTC Vive		Oculus Rift	HTC Vive		Oculus Rift	HTC Vive
Accuracy (cm)								
Inside	-	0.58±0.45		0.76±0.53	0.75±0.69		0.61±0.55	1.22±1.18
Outside	-	0.85±0.84		1.03±0.74	0.93±0.72		0.92±0.75	1.49±1.38
Jitter (mm)								
Inside	-	0.19±0.26		0.12±0.18	0.23±0.33		0.13±0.46	0.31±0.56
Outside	-	0.27±0.37		0.25±0.48	0.32±0.44		0.36±0.54	0.44±0.99

4. Controllers and Input Technologies

4.1 Game Controllers

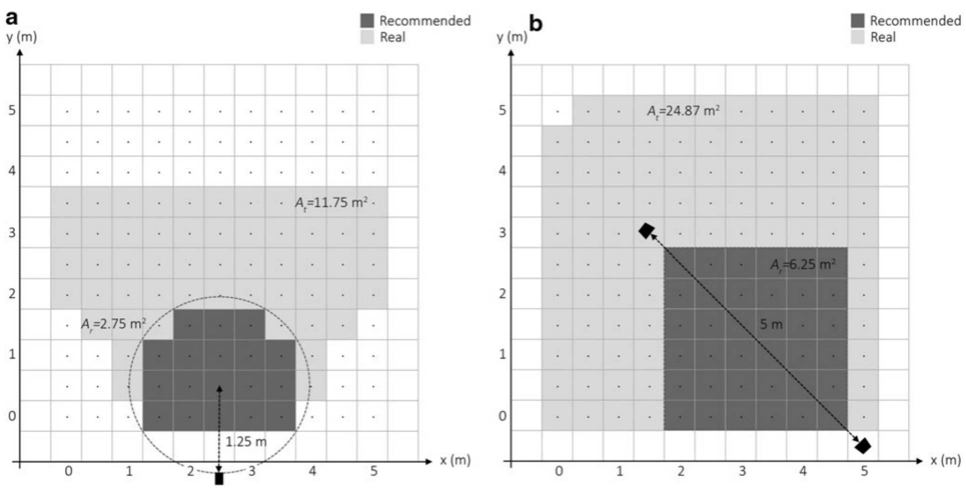


Fig 5. Result of comparison of the working area between Oculus Rift (left) and HTC Vive (right)

Game controllers are an integral part of all game consoles which fully fit the importance of interaction in games. As a kind of input devices, VR users can easily make some interactions through them, especially as they play a game that enhances the immersion of the VR experience.

The first game controller called “Control Box” in fig 6 was designed by Alan Kotok and Robert A. Saunders from MIT Tech Model Railroad Club for the game Space War [9-11]. It consisted of 2 two-way switches and a button. The two two-way switches control the left and right rotation and forward of the spacecraft respectively, while the button is the fire button.

Nowadays game controllers are mainly produced by three greatest game console manufacturers, fitting into their own game host products, including Dual Sense from Sony for their Play Station 5, Xbox Series X Controller for XBOX Series X and Nintendo Switch Pro for Nintendo Switch. Combining with their hosts’ different properties, they are favored by consumers as the game developing companies issue various types of games on each platform of the hosts.

Fig 6. Control Box

4.2 VR Controllers

In order to accomplish the interactive functions to virtual reality, VR devices also include controllers that allow people to move, grab, or make other actions. Some of the controllers also make sense on users’ position tracking, like PlayStation Move, the somatosensory controller for PSVR, containing advances motion sensors and trackballs that emit light of different colors, helping the camera receive the real-time space positions of players’ hands. There are 2 kinds of controllers respectively from Oculus and PlayStation in Fig 7. Comparing to the sticky shape of PS Move, Oculus Touch applied a bracelet-like design that allows cameras to track the user's hand, which provides a convenient grip for the user because it is also more ergonomic. Consumers that experienced Oculus Touch gave high recommendation, which strongly improved the immersive experience of VR [12].

(a) Oculus Touch (b) PS Move

Fig 7. VR Controllers from Oculus and HTC

4.3 The Tendency: Haptic Gloves

Technological gloves are able of measuring angles, pressure, tracking and haptic feedback [9]. The Dexterous HandMaster (DHM), on behalf of the earlier wired gloves, was originally developed as a controller for a robot hand. With sensors embedded and its great performance it became an irreplaceable instrument for fine work or clinical analysis [13]. The haptic gloves are also one of the most popular devices asked for VR and the most complex to develop [14]. Nowadays haptic gloves for VR usually embed thimbles and exoskeletons on the traditional gloves, collecting data from users for the hand motion capture research. The haptic gloves now cost a lot, but with the technical development and the reduction of their cost in the future, it is easy to infer haptic gloves will be one of the most common devices in VR, because of their flexible and sensitive sensors that fit users' fingers.

5. Conclusion

With metaverse developing, VR may usher in explosive development in the future. Sensing technologies make great sense in VR series, as various technologies are used on HMD, position tracking and input devices, sometimes combinations were applied on all of them, like some HMDs and input devices help track the information of users and analysis were conducted by the computer. At the same time, there are several aspects VR devices and sensing technology that are commercially successful could be advanced, as they cannot construct fairly immersive VR experience till now. Further research about sensing technology in VR may pay more attention to the immersion, which is the most important part of consumers who are trying to visit a real virtual world.

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