State of the Art of Virtual Reality Technologies

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Abstract—**In the past three years, the so-called second wave of Virtual Reality (VR) has brought us a vast amount of new displays and input devices. Not only new hardware has entered the consumer market providing affordable pricing models but also completely new technologies are being designed and developed. Additionally new concepts for handling existing problems on the hardware and software side of the VR technology are constantly being introduced.**

This software and hardware development is mainly lead by enthusiasts interested in the domain of VR opposed to the established scientific community, which already partially makes use of the newly available technology. Besides Head-Mounted Displays (HMDs), either cable-based or mobile, other devices like haptics devices, controllers, vests, omnidirectional treadmills, tracking technologies, as well as optical scanners for gesture-based interaction are gaining importance in the field of commodity VR. Most of these technologies are already precise and robust enough to be used for professional operation and scientific experiments.

The topics discussed are the common issues with the new technologies including the approaches to solve them as for example motion-to-photon latency, barrel distortion, and low-persistence displays. Additionally an in-depth analysis of the available solutions expected to hit the market is provided. A taxonomy categorising the current developments with the chosen implementation approaches will be given. The paper analyses the state of technological advancements in the field and provides an extensive overview on the current development considering the upcoming devices and the advancements from the software side.

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1. Introduction

When you read this publication, it will most likely be out of date. Current development in Virtual Reality (VR) technology is happening at unprecedented speed. Systems and applications in the domain are presented at a daily or weekly basis.

Fifty years have passed since Sutherland presented his vision of the Ultimate Display [1] mimicking the real world in all available senses. A vast amount of individual technologies supporting this sensory stimulation have emerged but it wasn't until 1989 when Jaron Lanier coined the term Virtual Reality [2] trying to aggregate the different concepts. This started a hype but also brought together the scientific community developing technology and algorithms to fulfil Sutherlands Vision. Although the initial euphoria collapsed after a few years, researchers saw the potential and carried on. Constant achievements have been published in conferences like the IEEE VR or ACM VRST and journals like Presence. Over the years, VR has evolved to an extremely useful technology for research and industry.

In 2012, nearly a quarter century after the first wave of VR a Kickstarter project named the Oculus Rift, with the purpose of providing an affordable high-quality Head-Mounted Display (HMD) to the public, was looking for funding and achieved the goal of $250 000 in less than 24 hours. This was the initial spark starting the so-called second wave of VR — the development we are currently facing. A vast amount of products are emerging and will be flooding the market trying to implement aspects of the vision of the Ultimate Display, but this time prototyping is much more affordable and research of the past 25 years is analysed in order to create efficient solutions.

In this publication, we give an overview of the current advancements in the field, focusing on the consumer hardware by categorising it and describing the technical approaches as well as the issues that are currently being dealt with.

These developments will ultimately affect the scientific community in a more direct way than the Kinect or the Wiimote affected the Human Computer Interaction (HCI) community. Those devices are great for experimental prototypes but we assume that the development in commodity VR will be as beneficial for the scientific community in an immediate way as is the development of graphics cards driven by the gaming industry. Recently nVidia and AMD have included features in their graphics boards supporting current and upcoming HMDs. Final technologies used in research will rapidly improve as displays and tracking hardware become mass produced and thus are available for low prices with a more robust and ergonomic design.

Due to the focus of this paper we will explicitly avoid the discussion about the current development of non-consumer devices like spatially immersive installations as CAVE-like[2] installations [3] or professional motion capture systems.

The paper is organised as follows. The next section will give an overview on state of the art surveys in the individual fields of VR, common taxonomies, books and other relevant resources. Section 3 presents a taxonomy illustrating and categorising the input and output devices. It is followed by sections describing the hardware and software developments in the VR domain taking an excursion into aerospace as an application area. Afterwards technological issues and current hot topics are discussed. Finally, conclusions are drawn.

Two appendices show the product details of input and output devices, which also include the references to the company or project websites. A third appendix gives an overview on the media resources providing information about the developments.

2. Related Work

Related Work is scarce and will be distributed over the paper if a close relation between a novel approach and existing research can be identified.

State of the Art Descriptions

A few state of the art reports or surveys trying to cover the whole VR domain exist. More recent ones are provided by Muhanna [4] who also introduces a taxonomy covering the different types of VR. He focuses on the academic and industrial field rather than the recent developments in consumer VR and puts a strong emphasis on CAVE-like systems. Zhou and Deng [5] provide a historical overview on the developments in the research domain but mainly concentrate in their state of the art survey on the technologies used for image processing to create virtual environments.

Taxonomies

Typically the available state of the art reports are focused on individual aspects of the field or on specific application areas. They often provide taxonomies illustrating and categorising the different approaches. Menus for Augmented Reality (AR) and VR environments in the whole Mixed Reality (MR) domain [6] have been explored by Dachselt and Hübner [7] who also provide a detailed taxonomy.

A taxonomy of Networked Virtual Environments (NVEs) has been given by Macedonia and Zyda [8] looking at communication and distribution topologies. Mania and Chalmers have provided a classification of communication and platforms [9].

Bowman has provided a variety of taxonomies for interaction [10] and for navigation techniques [11]. Early works by Mine [12] identify the key interaction and navigation in virtual environments.

Good generalised overviews are given by Gabbard [13] who provides guidelines for user evaluation including best practices for application design. Evaluation guidelines for Virtual Environments (VEs) have also been identified by Livatino and Koeffel [14].

Welch and Foxlin [15] give an overview on existing tracking technologies describing and comparing their advantages and disadvantages.

Books

On the other hand, vast amounts of books which give an overview on the field and the technology have been published.

Burdea and Coiffet focus on the hardware aspects of VR technology [16]. Hainich and Bimber describe display technologies in detail [17].

In the area of NVEs good overviews and details on the implementation of algorithms are given by Diehl [18] who clearly focuses on web technology but also providing a generalised overview on NVEs. Singhal and Zyda [19] describe the foundations of NVEs also addressing the specific problems of network communication relating to communication topology and data distribution. Steed and Oliveira revisit the topic of NVEs while targeting a student audience providing practical examples [20].

A recent generalised compendium is provided by Hale and Stanney [21] also giving details and solutions in the different application fields.

The current literature describing the VR development is scarce and reliable resources are few. Details on the first versions of the Oculus Rift are described in a book by Davies [22]. The VR Book by Jerald [23] tries to focus on both technology and HCI. A hands-on guide for the development of VR applications has recently been written by Toni Parisi [24].

Other Resources

Hardware producers provide information to the community on different channels. Additionally, many blogs, Facebook groups and podcasts have emerged. The most relevant communication platform in the community seems to be reddit[3].

In terms of conferences, meetings and exhibitions a community parallel to the scientific community has emerged. VR Meetups are happening in many big cities. The Meetup web pages[4] show currently over 250 regular meetup locations with more than 55.000 members all over the globe. Web pages like VRCasters[5] are streaming Virtual Reality Podcasts 24/7. A tabular overview on the current resources in consumer VR is given in Appendix C.

3. A Taxonomy of Current VR Hardware

When providing a taxonomy of the current VR hardware developments, the presented devices often exist only in a prototypical state; most of them are not yet commercially available and may even never be. Nevertheless, it is still possible to categorise the hardware and identify trends. More details on the actual devices will be provided in Section 4.

[2] CAVE^{TM} is a trademark of the University of Illinois Board of Trustees. We use the term CAVE to denote the both the original system at Illinois and the multitude of variants developed by multiple organisations.

[3] https://www.reddit.com/

[4] http://vr.meetup.com/

[5] http://vrcasters.com/

We follow the traditional approach of separating VR hardware into the two main categories of input and output devices. In most cases, we are looking ultimately at hybrid devices as for example an HMD which of course also provides input data with its additional tracking features. Thus we opted for a well-known tree visualisation shown in Figure 1. It is enhanced by icons illustrating the display and the input components reflecting the hybrid character of the device. It is of course arguable whether some devices should be in one branch or another.

As a display, we only consider devices which provide active sensory stimulation beyond the stimulation of just holding the device. Spatially Immersive Devices (SIDs) or other projection driven technology is not considered due to its lack of relevancy in the current developments. The upcoming devices are clearly focused at end-consumers, which suffer from spatial and monetary constraints not being able to afford installations like CAVEs. Auto-stereoscopic devices like lens grid or barrier displays are not considered either due to the stereoscopic quality and the low degree of immersion. Some devices can be combined (or are already equipped with) cameras and open their usage in the field of AR. When a device is predominantly used for VR purposes, it is included.

Output Devices

The main category in current display technology represents the **visual** displays. In terms of consumer VR they are all HMDs which are either *wired* or *mobile*. Other categories providing **haptic** and **multi-sensory** feedback are included as well in the taxonomy.

Mobile HMDs—In the mobile systems, we identify three sub-categories. All share the property of being wireless and being able to be used without an additional PC. In most cases, the application areas lie in entertainment - displaying 360° movies or panoramas rendered from a stationary point of view or alternatively interactive walkthroughs based on gaze directed navigation [25].

The first sub-category in the mobile displays we call “simple casing”; these displays are basically a frame for smart phones having additional lenses mounted at a reasonable distance. They fully rely on the technology of the smart phone used.

The second mobile sub-category consists of ergonomically designed smart phone cases, which contain significantly better optics and give more comfort of wearing.

An additional sub category is the mobile HMDs. The different Gameface prototypes which are stand-alone systems and do not need an additional PC or a smart phone. The approach presented by Gameface includes the compute system within the headset. This seems to be a promising approach. Auravisor followed this concept.

Wired HMDs— The second big display category are wired HMDs. The feature list of the wired HMDs is diverse and differentiation is beyond the traditional quality factors like resolution, Field of View (FOV) or weight. Some are equipped with cameras to allow for AR and can be used as video see-through displays, while others include eye tracking.

The current stationary HMDs are typically empowered by a 6 Degree of Freedom (DOF) tracking system provided by the manufacturer of the HMD and are connected to a powerful PC. They conceptually focus on sitting usage except one system, which promises room scale experiences.

In our taxonomy, we introduced specific sub-categories for room based experiences and displays which come with separate cameras. We believe that, as with the Gameface prototypes, more devices will follow this approach in the mobile section. In the future, displays using cameras for tracking might develop in the direction of mobile HMDs like the Gameface prototypes. Room scale tracking provides different experience, by allowing a more natural interaction with the virtual environment.

Haptic Devices— The haptic devices cross different areas. Several approaches exist in form of vests including vibrotactile elements, while other are clearly hybrid since they are implemented as a controller. All of these approaches are either body worn or carried and form their own sub-category.

On the other hand, development in the area of ubiquitous displays providing haptics feedback has been undertaken; an example would be VirWind.

Multi - Sensory Devices— Additional displays stimulating other senses, which generate tactile or olfactory feedback, exist as well. The suggested olfactory displays for the consumer market are body worn, either as an add-on to upcoming HMD solutions, or alternatively combined with the display component of the HMD. Ubiquitous olfactory systems as known from the research domain, for example implemented in SpotScence [26], have not yet been suggested.

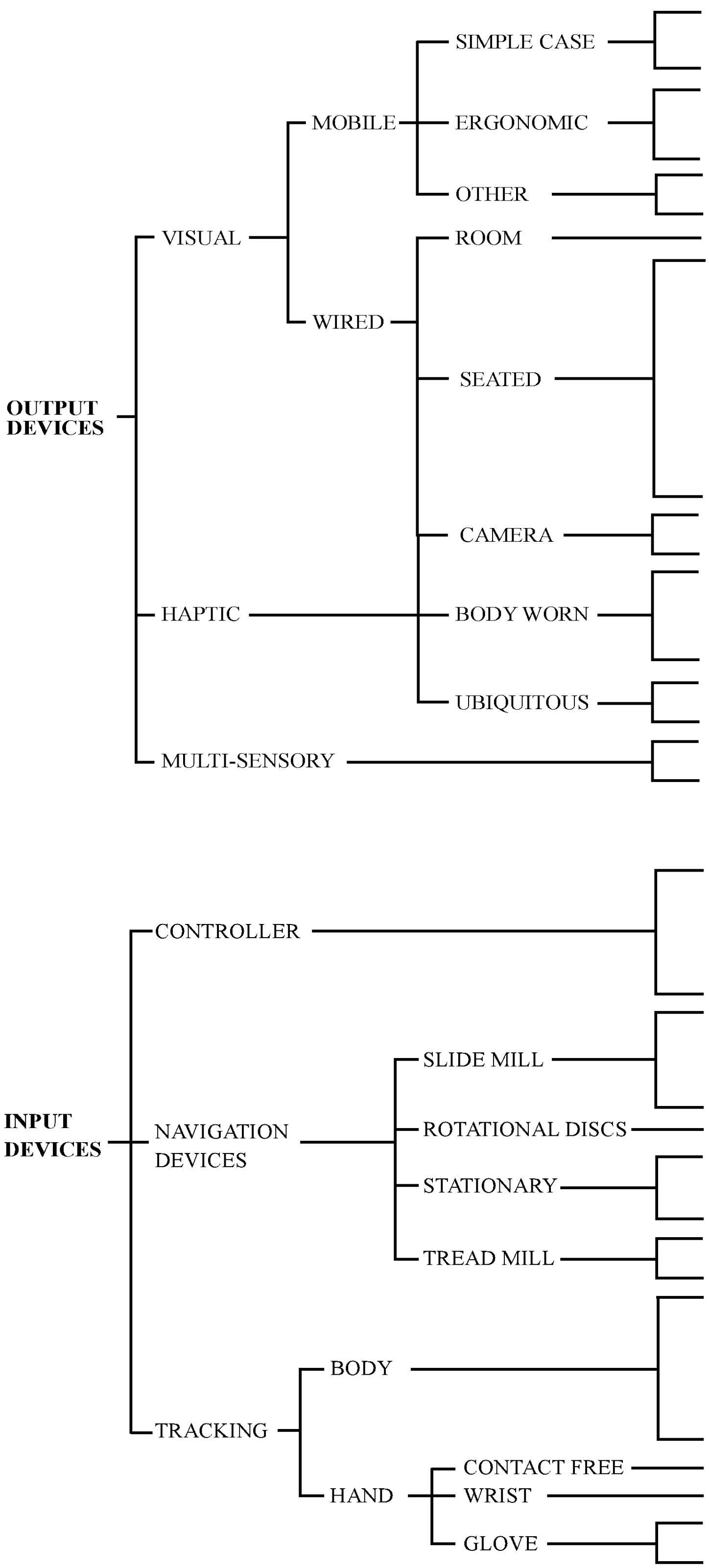
Input Devices

When we take a close look at our second big branch - the input devices - we can again identify three different sub-categories focused on input provision for HMD users. Thus, the main input category unsurprisingly is **controllers**. The second branch is constituted by **navigation devices** which allow the user to a more intuitive moving experience. Traditional controller input is often enhanced by **tracking** technologies which can further be divided in full *body* and *hand* tracking. The developments and technological choices in the input devices are more diverse than in the display branch.

Controllers—The controllers for HMDs are hand worn and provide discrete input in the form of buttons and continuous input by top-mounted joysticks or touchpads with additional 6 DOF tracking information. They may be wired or wireless. For the early applications for the existing HMD prototypes, conventional game controllers or keyboards and mouse interaction is used. A remarkable point is that always two similar controllers are offered to the user, one per hand. One controller approach stands out since it provides a significant amount for haptics feedback, going beyond the rumble features known from game consoles. The Reactive Grip is a perfect mixture between a haptic display and an input controller.

Navigation Devices—Navigation devices are used to give the user the illusion of moving through endless spaces and act as an input source for travelling through the virtual environment. While traditional treadmills allow motion in one direction the current developments in VR support motion on a two-dimensional plane - the Omnidirectional Treadmills (ODTs). Other technologies also exist, like the slidemills, which are passive low-friction surfaces, or devices designed for walking in place or sitting (which we consider stationary since the user is not actively walking forward).

Body Tracking—The posture estimation approaches focus on the actual posture of the user’s body or upper body as well



Output device	Tracking	Eye	Wind	Smell	Audio	Vibration	Touchpad
Google Cardboard							
VirtualVizor							
Wearality SKY							
Samsung Gear VR V1							X
Samsung Gear VR V2							X
Zeiss VROne							
Gameface Mark V	X						
Auravisor	X						
HTC Vive	X						
Oculus DK1	X						
Oculus DK2	X						
Oculus - The Rift	X				X		
PlayStation VR	X				X		
FOVE	X	X					
StarVR	X	X					
HDK OSVR	X						
Avegant Glyph	X				X		
AntVR	X						
Sulon Cortex	X						
VRvana Totem	X						
ARAIG					X	X	
KOR-FX						X	
TeslaSuit						X	
Subpac M2						X	
VirWind			X				
Feel Three						X	
FeelReal			X	X			
Nirvana Mask			X	X	X		

Input device	Tracking	Body	Head	Hand	Controls	Vibration	Touchpad
Grifta	X				X		
SteamVR Controller	X				X		X
Reactive Grip	X				X	X	
Half Moon	X				X		
Hydra	X				X		
Virtuix Omni							
Cyberith Virtualizer							
WizDish							
KAT WALK							
WalkMouse							
Stompz							
Roto VR							
VRGo							
Infina Deck							
Space WalkerVR							
STEM	X		X				
PrioVR		X					
Salto		X					
Perception Neuron		X	X				
ControllVR		X		X			
Ximmerse		X			X		
LEAP Motion				X			
Myo				X			
Gloveone	X			X			
Manus				X			

Figure 1. **A Taxonomy of the current hardware separated into input and output devices**

as on the gesture of the user's hand. The posture estimation in consumer VR can become a critical feature in order to provide a reasonable self-representation required in HMDs as demanded by Badler et al. [27]. A common implementation uses only magnetic tracking while others rely on Inertial Measurement Units (IMUs) combined with magnetic tracking.

Gesture Tracking—The approaches chosen for gesture tracking are diverse and range from data gloves, with strain gauges or fibre optics, which are worn on the hands over fully contact free technologies using optical tracking to wrist worn technologies using Electromyography (EMG) measurement.

4. HARDWARE DEVELOPMENT

The design and development of novel devices incorporating novel design approaches is happening in both the input and output devices at unprecedented speed. While the previous section gave an overview on the different categories of devices this section provides a more detailed description of the individual products and prototypes in the defined categories describing their unique features. A tabular overview of the devices providing specifications like resolution FOV and tracked DOF is given in Appendix A and Appendix B.

Visual Displays

Research in HMDs which display computer generated content started in late 60s with Sutherland's "Sword of Damocles" [28] consisting of a set of CRT-based optical see-through relay optics and mechanical tracking. Iterations of different optics and screens have been developed over the years. The HMD technology has been focused on resolution, weight, contrast and other attributes. Currently used display technology are LCD and OLED displays.

When we take a look at the HMDs in the MR domain traditionally three categories are seen: see-through displays using optical combiners, video see-through displays and classical VR HMDs, which fully isolate the user from the real world. An in-depth comparison of the AR see-through displays is given by Rolland et al. [29]. Some of the presented VR HMDs can be used as video see-through displays as well.

Mobile Head Mounted Displays—The mobile HMDs carry in most cases a common smart phone as a whole for display and processing of data. They provide a simple casing, which keeps the phone at a specified distance from the lens. Google developed the first devices of that kind. The Google Cardboard[6] follows the philosophy to act as a very basic viewer, not even allowing the user to strap-on the device. In order to provide basic interaction it is equipped with a magnet on the left side of the cardboard. The sensors of the phone detect the magnet motion. A vast amount of cardboard clones exist and are cheap and good for disseminating the technology. They differ for example in terms of lenses providing a large FOV or mounting. More advanced solutions are being distributed as well, providing a simple plastic casing, back straps or hats to mount the phones.

Samsung has developed high quality smart phone holders in cooperation with Oculus. The GearVR[7] provides an additional touchpad on the side of the case. The two available Innovator Editions as well as the first release version are limited to Samsung phones. Another ergonomic smart phone holder is the Zeiss VR One[8] which supports Apple Phones as well as Samsung Phones. Phone specific slide-ins are used to place the mobile devices inside the casing. Zeiss recently also provided a version following the approach chosen by Google - the VR One GX -, which is in terms of features fully compatible with Cardboard, also features a magnet and has no back strap.

Besides the smart phone holders Gameface[9] introduced a standalone mobile system which seems promising. Compute power running an Android OS coupled with an nVidia Tegra SoC graphics chip are directly integrated into the case. Besides the IMU tracking Lighthouse tracking designed for HTC room scale experience should be included as well.

Similar to Gameface recently the Auravisor[10] was funded. This device also carries the compute system inside the HMD to provide an untethered experience.

Figure 2. Three approaches for mobile HMDs. The Google Cardboard (left), The Samsung GearVR Innovator Edition (centre) and the Gameface Mark IV (right)

Figure 2 shows three examples for mobile HMDs. On the left side an original Google Cardboard is shown representing the simple cases, the centre shows the GearVR representing the ergonomic cases and the right side of the figure shows the latest prototype of the Gameface systems a standalone mobile VR System.

A still unsolved issue with the mobile systems is the limited interaction. Samsung is providing a Bluetooth game pad to support interaction with GearVR applications.

Stationary Head Mounted Displays—The stationary HMDs are besides their optical tracking all equipped with additional sensors. They contain accelerometers, magnetometers and gyroscopes and use sensor fusion to combine this information with the optical tracking. These devices are often built using existing display technology from the mobile phones.

The three big competitors are the Oculus Rift[11], PlayStation VR[12], and the HTC Vive[13]. All seem to have good chances on the market since the all provide their own online market place with an already established user base.

The Oculus Rift, which is probably the best documented of the devices, went through several iterations: the Developer Kit (DK) 1, the Crystal Cove, the DK 2, the Crescent Bay and finally the Rift. Both developer kits were available to the public, and have been extensively used in home-brew development as well as in research. Over 500 applications

[6]https://www.google.com/get/cardboard/
[7]https://www.oculus.com/en-us/gear-vr/
[8]http://zeissvrone.tumblr.com/
[9]http://www.gamefacelabs.com/
[10]http://www.auravisor.com/
[11]https://www.oculus.com/en-us/rift/
[12]https://www.playstation.com/en-us/explore/project-morpheus/
[13]http://www.htcvr.com/

are available for the first two prototypes on RiftEnabled[14]. The final version comes with detachable headphones.

In terms of the actual display, the HTC Vive provides similar specifications to the Oculus Rift. The main difference to the other wired HMDs lies in it's tracking range. Opposed to many other approaches the Vive is designed for room scale use allowing different application areas.

Oculus Crescent Bay and HTC Vive make use of Fresnel lenses to reduce the size and weight of the display. PlayStation VR is using aspherical lenses to reduce distortion in the centre.

While being able to walk during VR experiences adds immersion and realism, there are plenty of cost, engineering and safety considerations, which discourage it. Therefore, most hardware is pushing currently for a seated experience, where the user remains stationary. This eases tracking, avoids problems with tripping over cables or nearby furniture, and removes the need for treadmills or large rooms. HTC Vive, however, does allow a 5m x 5m space to be tracked, allowing limited walking within the virtual space.

While OSVR[15] is mainly focussed on providing a common software platform for VR, they also produce their own headset. It has adjustable lenses.

Exchangeable lens sets have been used for the first versions of the Oculus Rift and the Zeiss VR One in order to adapt the magnification.

The most prominent wired HMDs expected to hit the market in 2016 are shown in Figure 3.

Figure 3. The most prominent wired HMDs, the Rift (left), the HTC Vive (centre) and the PlayStation VR (right)

An approach using eye tracking to allow foveated rendering or integrating fully hands-free interaction is the FOVE[16] HMD. By tracking the users eye and determining what he is currently looking at, several features like interaction, rendering depth of field, foveated rendering, and rendering of the gaze directions of the remote users on their avatars in multi-user environments [30] can be implemented. Early attempts in eye tracking for HMDs have been undertaken by Duchowski [31] to support aircraft inspection.

Also, approaches exist which try to cover extremely large areas of the FOV by using two high-resolution displays and aligning them in a slightly tilted way. StarVR[17] is an example for such an approach which provides an FOV of 210°x130° at a resolution of 2560x1440 pixels per eye. They incorporate Fresnel lenses to achieve this FOV and keep a reasonable display size. It has recently been announced that the StarVR will also support eye tracking.

Sulon Cortex[18] is an approach using additional cameras that can be used as well in the AR domain or combining both areas of the MR continuum. So far, it is still cable-bound which will most likely change if the AR domain will be supported.

The VRvana Totem[19] is equipped with cameras as well, which are predominantly used for inside-out tracking. With basic button interaction on the device, the video stream can be switched between the real and virtual world. Parts of the processing, e.g. pre-lens distortion and sensor fusion, is done on hardware inside the device. The captured video streams can be used as well to explore the whole MR domain. They could be incorporated to provide a reasonable self-representation as suggested by Bruder et al. [32].

Avegant Glyph[20] uses in-eye projection with the help of a micro mirror array. It is equipped with 6 DOF IMU tracking. Headphones are integrated in the display. Ultimately, it is designed to support mobile devices as a driving compute system. Although the used technology provides high contrast ratios, the FOV is very limited.

AntVR[21] has an adjustable IPD and makes use of aspherical lenses. It comes with an additional controller, which is fully reconfigurable in shape and functionality.

Haptic Displays

Haptic displays are a vast and common area often combined with visual displays in the scientific VR community.

Vests—In the domain of body worn haptic displays, force feedback vests have established a market. Early versions like the Auralizer in the 90s make use of the audio output generated by the system and transfer the sonic waves into vibration. Haptic vests or belts have also been used in a variety of research projects where they were used for collision feedback [33] or as navigational aids. Art projects have been implemented making use of a vest to provide co-presence in a networked virtual environment [34].

A vest provided by KOR-FX[22] uses a simplistic approach transforming audio signals into haptic feedback. The connection between the vest and the compute system is realised via the audio output. The audio signal is processed and transmitted as vibration data to be finally rendered by the vest. The Subpac M2 [23] is conceptionally very similar to the KOR-FX. An additional version is available, which can be placed on seats supporting a seated experience.

A rather sophisticated solution has been chosen by ARAIG[24]. ARAIG provides feedback on multiple levels. It integrates speakers along the vests collar to provide surround sound to the user. Vibration feedback, audio feedback and electrical stimulation (to contract specific muscles and simulate touch or hits) is applied on the user.

A second system based on electrical stimulation is the Tes-

[14] http://www.riftenabled.com/
[15] http://www.osvr.org/
[16] http://www.getfove.com/
[17] http://www.starvr.com/
[18] http://sulontechnologies.com/
[19] https://www.vrvana.com/
[20] http://avegant.com/
[21] http://www.antvr.com/
[22] http://korfx.com/
[23] http://thesubpac.com/
[24] https://araig.com/

lasuit[25] wich comes with 52 or 16 channels which is also supposed to render heat and cold. Compared to the other systems it is a full body suit.

Ubiquitous— A planned device is the Feel Three[26] motion platform, which is based on the concepts introduced by Kumagain [35] by inverting the original setup of a robot moving on a ball. With this device, the user is placed in a chair located inside a bowl. The rotation engines connect directly to the panelled spherical shell, which surrounds the device, so the device can be rotated freely. The only limitation to this are the number of panels installed and safety considerations when the user is not strapped to the chair.

A ubiquitous wind display, the VirWind, which places four ventilator pillars in space surrounding the user is also currently under development. Each pillar is equipped with four ventilators. Early approaches using ubiquitous wind displays to increase presence have been developed by Moon and Kim [36].

Multisensory Displays

The current development has also brought exotic displays from the olfactory and haptics domain onto the market.

Masks like Feelreal[27] can be attached directly underneath the common HMDs (wired and mobile) and provides seven different scents to further immerse the user. Cool and warm air can be blown in the users face and an ultrasonic ionising system is used to generate water mist. The device provides haptics feedback with the help of vibration engines and a microphone for communication to the outside world. While the Feelreal VR mask is used as an extension for existing HMDs a standalone approach, also integrating the displays is the so called Nirvana mask. The Nirvana mask integrates smart phones in a similar way as the ergonomic mobile HMDs. The approaches implemented by Feelreal combine, similar to the solution presented by Matsukura et al. [37], wind and odour but they ultimately remind of Morton Heiligs Sensorama [38].

Input Devices

The development of input devices is, as with output devices, very diverse. We observe a usage of devices that were already available before the second wave of VR which now find their use in the community.

Controllers— On first sight, the development of input controllers seems to be an enhancement of traditional game controllers having buttons, triggers and joysticks by adding 6DOF tracking. This observation might be true for already exiting devices now used in the VR context like for example the Razor Hydra, but the other upcoming controllers provide completely new approaches. Figure 4 shows three controllers introducing novel concepts for VR interaction.

The Half Moon controllers also known as Oculus Touch have capacity sensors which allow for basic gesture recognition depending which finger actually touches the device. A Half Moon controller has a loop surrounding the actual grip, which is used for optical tracking. It puts the centre of gravity of the device well in the centre of the hand.
A decision irritating the community was the delivery of an XBox controller for the Oculus Rift consumer version to support game developers already working with game controllers. The 6DOF Half Moon controllers are shipped separately.

The SteamVR controller for the HTC Vive use touchpads instead of joysticks and is tracked with the Lighthouse system. The touchpad technology is high precision and based on their Steam Controllers.

Reactive Grip[28] offers fine-grained haptics feedback and can be equipped with a STEM sensor or other available solutions for 6 DOF tracking. Upward and downward forces can be displayed as well as torque. Originally designed with four it utilises three sliding plate tactors on the grip [39].

Figure 4. The Oculus Half Moon (left), the Reactive Grip (centre), and the SteamVR Controller (right)

Grifta[29] for example is a controller, which is fully reconfigurable. It can be split from a two-handed gamepad-like controller into two individual one-handed controllers. It provides a vast amount of buttons, triggers and joysticks. Basic 6DOF tracking can be added to the controller by attaching additional IR-LEDs and using a camera.

Navigation devices— The navigation devices range from ODTs, over slide mills and chair based interfaces to foot tracking. The concept of two-dimensional treadmills has been explored in the late 90s in the context of VR by Iwata et al. [40]. A direct successor to this approach is the InfinaDeck[30] which provides similar to Iwatas' original treadmill a set of treadmills aligned perpendicular and turning on a single treadmill. The InfinaDeck is designed to support walking speeds of 5.6 km/h in the early prototype.

The Space Walker VR[31] installation is a traditional treadmill which can be rotated as a whole. A harness is placed around the user to give him additional stability.

An alternative solution using a circular walking area is the the WalkMouse[32] treadmill. It provides a surface with active wheels on which the user is able to walk freely. The maximum walking speed on this system is 0.5 m/s.

Other systems use low-friction surfaces and let the user slide on these surfaces. The Virtuix Omni[33] is a concave low-friction platform for which special shoes, which have a straight line of knobs attached to the sole, are required. The user wearing the shoes slides with the knobs through slits in the platform. This approach provides stability and a natural gait. Additionally the shoes are tracked with IMU sensors. An adjustable harness guarantees the stability of the user.

[25] http://www.teslasuit.com/
[26] http://www.feelthree.com/
[27] http://feelreal.com/
[28] http://tacticalhaptics.com
[29] http://www.playgrifta.com/
[30] http://www.infinadeck.com/
[31] http://spacewalkervr.com
[32] http://www.walkmouse.com/
[33] http://www.virtuix.com/

Similar design choices can be found with the Cyberith Virtualizer[34]. The Virtualizer provides a circular low-friction flat base plate. Opposed to the Virtuix Omini, the harness is attached to a ring, which can be moved dynamically in the vertical direction which allows crouching and jumping in the device. Sensors are integrated in the ring, based plate and the frame of the installation. No additional shoes are required; overshoes can be worn to guarantee the low friction.

Other solutions are KAT WALK[35], which tries to be as unrestrictive as possible by placing the fixation of the harness above the user and WizDish ROVR[36], which is again closer to the concept of the Cyberith Virtualizer.

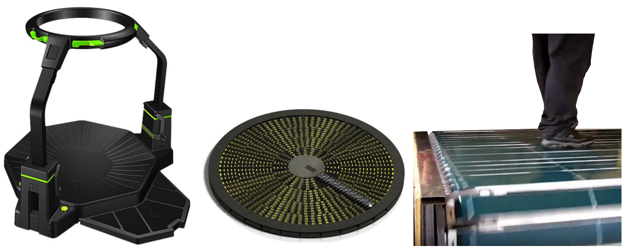


Figure 5. **The Virtuix Omni (left), the WalkMouse (centre), and the InfinaDeck (right)**

Figure 5 shows some example approaches of navigation devices. A low-friction slidemill on the left, an approach using active wheels and an ODT.

RotoVR[37] is platform-based interface which allows rotation of the user. By integrating a chair it follows partially the concepts of ChairIO [41]. Although it is restricting the users freedom on the one hand by placing the user on a chair or standing on a platform other restrictions can be avoided like for example cables tangling from the users HMD can be connected to the PC below allowing for rotation of the whole system.

Even closer to the CharIO concept is the VRGo interface[38]. It is also a chair interface that can be connected as an normal joystick or game pad controller. It communicates with the systems via Bluetooth and is activated by tilting.

Another approach for foot-based input is implemented in Stompz[39] which is a controller supporting the walking-in-place metaphor [42]. Similar systems have be used in research for example in ShoeSoleSene [43].

The Lighthouse tracking introduced by Valve has launched a controversy considering navigation devices. With Lighthouse, natural walking in room space (5 x 5 metres) is available without restrictions, but limited by the walls. On the other hand, navigation devices allow walking through virtual infinite space, but constraint the users locomotion in most cases by placing a belt or frame around him.

Posture Capture— In professional research environments, posture capture is typically performed with optical marker tracking. A variety of system are used although their application area is mainly in digital games and movies. Motion capture is important for three different areas. Interaction, user representation in remote environments and with HMDs also self-representation of the user.

STEM[40] a magnetic tracking system based on concepts introduced by Raab et al. [44] was the first tracking solution proposed for consumer VR. It provides a set of sensors as well as two wireless controllers for left and right hand usage. Depending on the chosen configuration head, hands and legs are tracked. The sensors can also be integrated into other controllers like the first Reactive Grip prototypes. The tracked area covers an 8 foot radius around the base station, which can also be used in a wireless mode. The latencies according to Sixsense range in the area of 5ms.

PrioVR[41] makes use of magnetometers and accelerometers. Different version provide 8, 12, or 17 sensors, distributed on upper body and whole body at different resolutions. It is like STEM also wireless and comes with two controllers.

Similar to PrioVR, Ximmerse[42] is a body tracking system relying of IMUs, which can be placed freely on the body. Additional external stereo cameras can be used to track the Ximmerse controllers.

Another motion capture system is the Salto Suit [43]. This system also relies on 19 IMUs at a fixed location on the suit.

The Perception Neuron[44] motion capture system is like PrioVR based on IMUs which are very light weight and can be attached over the user's body. One to 32 sensors are supported per system. Controllers are not provided by the system but optional gloves can be used to attach IMU sensors on the fingers in order provide gesture tracking which makes it a hybrid system between body and gesture tracking.

The Control VR[45] system is also a hybrid posture and gesture tracking system; it combines optical, inertial and electromagnetic tracking, while attached data gloves use fibre optics to measure the finger positions.

Figure 6 shows some exemplary devices used for body tracking. Ranging from magnetic sensor based tracking over to IMU based tracking supporting gesture tracking.

Figure 6. **The STEM (left), the PrioVR (right), and the ControllVR (centre)**

Gesture Tracking—The area of gesture capture offers new input approaches for VR. Gestures are captured either optically, via biofeedback or with data gloves. Data gloves based on the original concept by Zimmerman [45] are finding a new market. Typically, they are based on strain gauge technology

[34] http://cyberith.com/
[35] http://www.katvr.com/
[36] http://www.wizdish.com/
[37] http://www.rotovr.com/
[38] http://www.vrgochair.com/
[39] http://www.stompzvr.com/
[40] http://sixense.com/wireless
[41] http://www.priovr.com/
[42] http://www.ximmerse.com/
[43] http://salto3d.com/
[44] https://neuronmocap.com/
[45] http://controlvr.com/

using fibre optics.

Although not initially designed for VR input the Leap Motion is a device, which has found many applications in consumer VR. Leap Motion[46] is an optical hand tracker based on two cameras and infrared LEDs covering a hemisphere on top of the device. Special kits to mount the Leap Motion on an Oculus Rift are available. These setups are used for interaction, hand representation in the VE as well as using the Oculus Rift as an AR display.

Myo[47] measures the electrical signals travelling across the user's arm and transforms them into gestures. Similar to the Leap Motion the Myo was not designed as a VR input device. It is additionally equipped with a magnetometer providing information on the orientation of the users wrist and accelerometers giving information on the motion speed and direction. It can provide additional vibration feedback.

Glove One[48] provides 5 actuators per hand. Additionally conductive fabric zones are used for discrete input. Thus it allows for interaction and navigation mechanisms as described by Bowman et al. [46] which could be applied as well for the Glove One.

The Manus[49] dataglove is a wireless device, which communicates via Bluetooth to the VR system, which could be as well a mobile HMD. It provides on each glove a sensor using IMU technology giving information about the position and orientation of the whole hand.

Figure 7 shows some exemplary approaches for hand tracking. Ranging from completely contact free via wrist bound sensors to data gloves.

Figure 7. The Leap Motion (left), the Myo (centre), and the Glove One (right)

5. Software Development

In the area of software development, we give a brief overview on how VR software can be developed for the consumer market and additionally describe approaches from the scientific community. We give an outlook into applications used for collaborative work and especially applications in the area of aerospace.

Open Platforms

Many open platforms for software development are used in the current development. While PlayStation VR is focused on the entertainment market and does not plan to open their interfaces to the public, other hardware manufacturers like Oculus and HTC have released their SDKs.

[46]https://www.leapmotion.com/
[47]https://www.thalmic.com/
[48]https://www.gloveonevr.com/
[49]http://www.manusmachina.com/

Oculus provides a constantly updated SDK[50] for creating prototypes and involving the community in the application development process. They made the software and the specifications of the DK1 publicly available under GitHub[51].

Valve provides an API with Steam access (their online distribution platform) and one independent of Steam - the so-called OpenVR SDK[52] which is also available under GitHub.

Often, the devices come with their own SDKs closely bound to the hardware, which calls for standardisation to guarantee a cross device development. Such an approach combining open source hardware with open source software and a strong desire for standardisation is given by OSVR[53].

Only limited effort has been paid to integrate platforms which are well established in the scientific community, e.g. the Virtual Reality Peripheral Network (VRPN) [47] allowing input device abstraction. The only VRPN-supported input device in the current development is the Razor Hydra.

Game Engines

Currently established game engines supporting the Oculus Rift are Unity[54] and the Unreal Engine 4[55]. An overview on the available Unity projects and Unity VR development in general is given by Liwones [48]. The current Unity version also supports mobile development for example for the GearVR and a plugin communicating with the HTC Vive is available.

The integration process of Oculus Rift in Unreal 4 is described by Whiting et al. [49].

Crytek is also working of a release of the CryEngine[56] supporting VR devices.

It is worth noting that due to the increased rendering requirements of virtual reality devices, developers need to apply some tricks to decrease complexity. However, many of those which work well in desktop environments cannot be used in VR, as they become visible. For example, standard normal maps look like wallpaper, and sprite particles and tessellated geometry are noticeable, so care must be taken to only use them when sufficiently far away from the user.

But also in the scientific community game engines have been used to create VR environments as for example by Jabcoson [50] with an Unreal Tournament port. Compared to traditional VR frameworks like AVANGO [51], VRJuggler [52] or inVRs [53] the game engines that are adapted for VR usage have a variety of advantages. They follow the approach of providing usability and a vast amount of features for the developer. The VR frameworks from the research domain set their focus on the support of SIDs and other multi-display installations; they often provide predefined interaction and navigation behaviour known from the scientific community.

[50]https://developer.oculus.com/
[51]https://github.com/OculusVR/RiftDK1
[52]https://github.com/ValveSoftware/openvr
[53]http://www.osvr.org/
[54]https://unity3d.com/
[55]https://www.unrealengine.com/
[56]https://www.crytek.com

Web Development

WebVR[57] made a framework available to use WebGL within the firefox web browser to provide a virtual reality experience. Currently, the Oculus Rift is supported, although the framework is still in early development stages.

360° movies may not be considered VR since they do fulfil the constraint of real-time interactivity in a very limited way by only allowing the change of the viewpoint. Nevertheless, these videos have already found a wide adoption by the community and are supported inside web browsers. Currently, youtube as well as Facebook allow to display 360° movies. With HMDs, head tracking can be used to change the orientation of the camera during these movies. With this approach, content creation is comparatively easy if the hardware is available. It is a good entry point to excite audiences for HMDs.

Multi-User Experiences

As already seen in the related work section of this paper, multi-user environments always have been an important topic in VR. Community platforms supporting HMDs are consequently increasing in numbers. The most important ones are VRChat[58] where enthusiast discuss VR related topics and High Fidelity[59] which can be seen in many ways as a spiritual successor to Second Life.

Design Approaches

Many of the applications follow conservative approaches which try to avoid cybersickness [54, 55] issues. Cybersickness seems to be the biggest concern for the hardware manufacturers when hitting the VR market.

Cockpit views are common to provide a static frame of reference and solve the cabling problem since the user is to be seated simply by the design of the application. First person view seems to be avoided in many cases. A comfort zone in hands reach of the user provides space to place 3D avatars, which is the preferred perspective in many of the Rift line up applications.

An issue with which many developers are fighting is the scale. In traditional 3D worlds on 2D displays, scale is not as important as long as it feels correct in the 2D projection. When developing for stereoscopic 3D content developers have to take into account a different life-like perception of scale.

Motion is in most cases forward and the duration of acceleration is often short. Constant perspective movements should be avoided. Oculus has released a best practice guide explaining these and other problems in their documentation in order to improve the initial output of the early stage VR developers.

Applications in Aerospace

Virtual reality has been used within aerospace for telerobotics at NASA since 1986 [56]. Exploring planetary environments using virtual technology was also an early use case [57]. Furthermore, VR is used to train astronauts for the last 25 years [58]. The same yields at ESA for space telerobotics and astronaut training [59]. Experiments on disorientation due to microgravity environments have also been performed by JAXA [60]. Roskosmos is also using VR techniques for astronaut training.

An overview of the different virtual reality systems used by space agencies can be found in Stone et al. [61].

Current applications in Aerospace specifically in the domain of space are of an educative nature. Titans of Space[60] for example gives an overview of the planets and moons inside our universe, where the user is able to travel between objects. In *The Apollo 11 Experience*[61] users are able to experience the Apollo 11 mission from different viewpoints. The SpaceVR[62] project plans to send a 360° camera system up to the ISS in order to stream video to paying viewers. NeosVR[63] is a general e-learning platform, which provides applications illustrating spatial relations on a cosmic level.

In the area of flight simulators the FlyInside[64] project offers an integration of the Oculus DK2 into Microsoft's Flight Simulator X and Lockheed Martins Prepar3D.

6. TECHNOLOGY

The technological challenges discussed in the field of consumer VR deal with display quality to increase the experience and latency issues in order to reduce potential cybersickness. All of these problems are well known in the scientific community but often novel approaches are undertaken in consumer VR to solve them. Of course, a variety of other issues related to specific devices especially in the area of input devices are discussed as well.

Display Related Topics

Current HMDs take advantage of the technology advancements of mobile phones and tablet displays. Resolution, pixel density and contrast values have significantly improved since the rise of the smart phones and tablet computing. These mass produced consumer displays are used in the current HMDs, not only in an immediate way, by placing a smart phone in front of the lenses, but also by using the actual smart phone display as a final HMD display. The Oculus DK1 uses for example a Galaxy Note 3 display from Samsung.

Resolution, technology and sub-pixel placement—While resolution is often cited in the technical specifications of VR hardware, there are other details, which also have a strong effect on visual quality.

Each pixel is composed of sub-pixels with pure red, green or blue components, which can be arranged in different ways. Classic RGB sub-pixels repeat the RGB pattern. An alternative is PenTile [62], which uses other patterns, either a white sub-pixel, or a second green sub-pixel. PenTile patterns have a lower perceived resolution in certain cases, but have more room for miniaturisation in the future. Other systems use an additional yellow subpixel instead [63].

With respect to the technology, LCD displays use a backlight with a coloured mask, while OLED use organic LEDs to enable a better colour gamut and true blacks.

[57] http://mozvr.com/
[58] http://www.vrchat.net/
[59] https://highfidelity.com/
[60] http://titansofspacevr.com/
[61] http://immersivevreducation.com/
[62] http://www.spacevr.co/
[63] http://neosvr.com/
[64] https://flyinside-fsx.com/

Some researchers have used two standard displays with a half-pixel vertical and horizontal offset to obtain a quadruple-resolution display [64]. Their solution is especially suited for HMD use, although no current prototypes make use of this technique.

Low-Persistence Displays—One of the issues with the first available prototype of the Oculus Rift was the persistence of the displayed content. This was caused by LCD display technology, where pixels under constant illumination lead to a perceptible smearing during rotation.

The issue is not present any more when using low-persistence displays incorporating OLED technology. In this case, low exposure times reminiscent of strobe lights produce a flashing image, which are sometimes still distracting but give improvements in comparison to blurry images produced by previous displays. An example for this is given in figure 8 which shows a comparison of the two Oculus prototypes with LCD and OLED technology during motion.

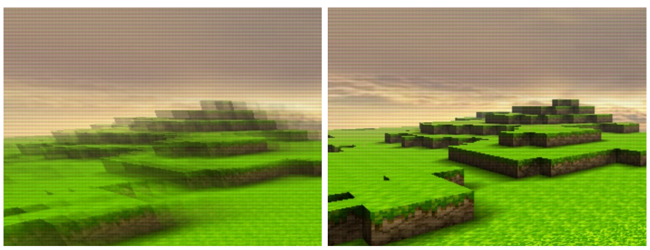


Figure 8. High-persistence image (on the left) and low-persistence image (on the right) in motion, generated with the Oculus simulator[65]

Current displays used in latest-generation HMD use a persistence no longer than 3 ms for 1k x 1k resolution with a 110° FOV. In particular, the Oculus DK2 OLED display has 2-3 ms —specifically 2 ms@75 Hz, 3 ms@72 Hz, full persistence@60Hz (16.7 ms)— by using an overclocked AMOLED display from the Galaxy Note 3. The Crystal Cove Prototype has a persistence under 1 ms, while the Sony Morpheus (Playstation VR) uses full persistence (8.3 ms@120 Hz), but has a low-persistence capable OLED display. Finally the HTC Vive has 2 ms@90 Hz [65].

With respect to smartphone-based HMDs, the persistence depends on panel technology. LCDs are full persistence, while OLED and AMOLED displays can be low persistence. Current displays have 2-3 ms persistence or higher.

Screen Door Effect—The so-called Screen Door Effect is well known from projection technology. It describes the visible gaps between the actual pixels. Its effect becomes visible when displays are scaled through lenses. In current VR technology, especially with HMDs, this is irritating for some users. Diffuser screens can be applied to reduce the effect, with the consequence of blurring the image (for example, general-use matte screen protectors have been used). In the future, the screen door effect will be solved by increasing the resolution of the displays until the gaps are no longer visible.

Algorithmic approaches have been applied to projector technology and might be applicable also for HMDs [66].

Figure 9 illustrates the screen door effect.

[65]http://vr.mkeblx.net/oculus-sim/

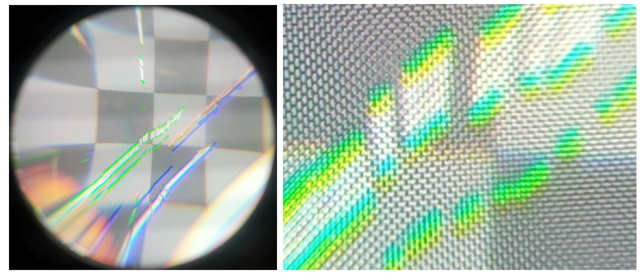


Figure 9. Screendoor effect on Oculus Rift DK2. Left: complete eye; Right: enhanced view of centre.

One drawback of using diffuser displays is accommodation of the eye lens.When the image becomes blurry, most users attempt to compensate by constantly trying to refocus. This again leads to the eye strain problem.

Lens Related topics

All current HMDs use lenses to increase the quality of the visualisation but this requires some careful considerations which are discussed in the following.

Barrel Distortion— Using lenses to zoom a planar image causes distortion of the image. When perceiving the image through regular lenses it results in so-called pincushion distortion. Straight lines seem to bend inward to the centre of the image which gives it the appearance of a pincushion as illustrated in Figure 10.

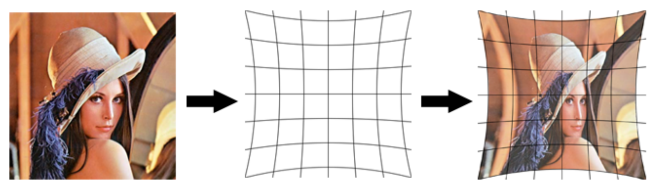


Figure 10. On the original image (left) a pincushion transformation (centre) is applied which leads to a distorted image (on the right)

This distortion has to be compensated by pre-distorting the image inversely. The inverse distortion of a pincushion distortion is a barrel distortion. Figure 11 shows the process of inversely distorting an image with an already applied pincushion distortion.

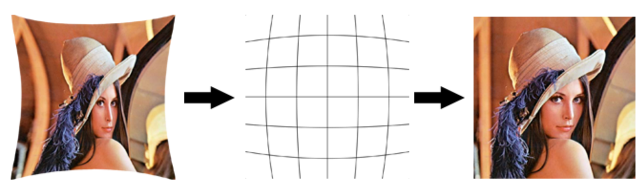


Figure 11. An originally pincushion distorted image (left) the barrel transformation (centre) and the resulting undistorted image (on the right)

Distortion is typically radial but does not necessarily have to be, depending on the lenses. Usually, this type of pre-distortion is performed with the help of shaders in the frame buffer after image generation. An additional result of distortion and correction is the loss of screen space in which pixels are displayed. Different approaches exist depending on the used products and APIs. For the HTC Vive a lookup-texture is utilised to perform distortion.

Chromatic Aberration—When using lenses to magnify displayed content, colour shifts can take place. This is due to the lenses having a wavelength-dependant index of refraction and produces colour smearing and distortion. This problem can also be found in the field of photography. An example is given in Figure 12.

Figure 12. An example for chromatic aberration

This can be corrected by performing one render-pass per colour layer, which obviously leads to a performance loss. This step is typically implemented in shaders.

Lens type—Some specific lens types can help reduce the size and weight of HMDs.

Fresnel lenses reduce the size and weight of lenses by dividing it into circular segments and consequently reducing the width of the lens without changing the surface curvature. This reduction in size and weight often outweighs created discontinuities in the segment boundaries that produce some stray light. Those lenses are used in Oculus Rift, Crescent Bay and in HTC Vive.

Aspherical lenses Most lenses use cylindrical or spherical surfaces. However, those come with image aberration and sometimes the need to stack multiple lenses to obtain the needed effect. In contrast, aspherical lenses may use non-constant curvatures. This allows a reduction in spherical aberration and may also reduce the number of needed lenses, reducing further size and weight of the devices.

Fixed IPD caveats—For the case the IPD is not physically adjustable, the user will look into the lens from a side angle. This will produce image distortion and eye stress. However, if the correct IPD is known, the rendered image can be modified in software to avoid the problem.

Tracking Systems

Traditionally, wide spread systems for tracking, like mechanical, magnetic or acoustic systems loose relevance in the current developments. The present issues are sensor fusion and the reduction of tracking latencies. The most prominent tracking technique in the current VR market is to optically track infra-red (IR) diodes.

The cable-bound HMDs use additional information from gyroscopes, accelerometers and magnetometers to stabilise information gained from the optical tracking. Sensor fusion techniques are in this case used to determine the position and orientation of the HMD.

Since most smartphones currently have gyroscopes, accelerometers and magnetometers that can be accessed programmatically, the Mobile HMD systems exploit these to keep track of user's position and orientation.

Two different general approaches exist for determining an object's position or orientation: *outside-in* and *inside-out*([67], chapter 4, section 4.3). In the case of *outside-in*, trackers (e.g. cameras for optical tracking is used)are fixed in the scene while markers are positioned on the tracked objects. For *inside-out*, the optical trackers are fixed on the tracked objects whereas the markers are fixed in the environment.

Standard IMUs now contain 3 accelerometers, 3 gyroscopes and 3 magnetometers, placed orthogonally to each other in order to provide six degrees of freedom. However, temporal dependent drift is still a problem. Some devices use visual tracking by an external camera to mitigate this. For an example, the Oculus Rift using this technique and 1kHz sampling frequency [68] reaches approximately 1 mm or $0.25°$ accuracy.

Lighthouse—A real surprise for the community was the introduction of the Lighthouse tracking system, which achieves latencies below 10ms. Lighthouse uses a set of base stations projecting laser fans horizontally and vertically into the tracked area. The tracked objects contain a comparably large amount of sensors, registering the hits of the lasers. Reflections from walls and other objects are also considered.

Optical Tracking—Opposed to the common approaches used in industry and academia where passive retro-reflective markers are used and IR light is projected into the tracked area, the camera based approaches in the upcoming systems use active IR-LEDs on the objects to be tracked.

Motion-to-Photon Latency— Motion-to-photon latency is a term, which is newly used but describes the well-known problem of the overall system lag. Tracking frequency is required to achieve precision, but the more interesting question is: "How long does it take from actual user motion to an adapted display". This aspect is relevant for interaction but also has great impact in the area of Cybersickness. In traditional VR installations, the tracking pipeline consists of a variety of steps, often including network communication, whereas with current HMD technology, the sensors are communicating directly with the system running the application or are even located on those systems.

Current experiments show that as long as latency stays consistently under 20 ms, the system works and no undesirable effects appear. 25 ms latency might also work, when combined with prediction.

Time Warp— Rotation latency is the most noticeable issue but can be reduced by time warping. Here, after a scene is rendered, the IMU is queried just before the monitor vertical synchronisation signal (vSync) and a reprojection is performed [69].

Asynchronous Time Warp—In real-time applications, a common issue is the problem of not having the rendered frame available, when it is to displayed. This typically leads to a reduced frame rate or perceivable frame drops. Being irritating in desktop environments this leads to even bigger problems in immersive environments when head-tracking is used.

To overcome the problem of missing vSync, which normally would mean presenting the same frame twice (with the corresponding increase in latency), the asynchronous time warp technique can be used. In that case, two rendering contexts are used, one for scene rendering and a high-priority one for timewarping. The use of this high-priority context makes sure the reprojection is ready in time for vSync [70]. Nvidia graphics cards are required at the moment to implement the technique.

Prediction— Time Warping relates to dead-reckoning and client side prediction. Predictive algorithms are well known in the field of simulators and networked virtual environments. They are not too common when used for adjusting the user view.

Pre Rendering—Motion-to-Photon latency can be minimised by querying sensors multiple times. For example, game logic can use a first sample, rendering can use a second sample, and a final per-pixel rotation at the end of the rendering can use a final sample to reduce latency greatly. Prediction can be used to further reduce the perceived latency [49]. The technique is called pre-rendering because primitives are sent to the graphics card before the exact camera parameters are known. This also means that estimation error may leave us with some pixels, which should be rendered and of which we have no information. Rendering to a slightly larger buffer than the screen resolution can help in these situations, and since this larger buffer is required anyway by the post-processing used to avoid lens distortion, the performance decreases are negligible. Oculus, HtC Vive and Sony all make use of pre-rendering techniques in order to decrease latency.

Input Generation

In addition to classical input devices such as gamepads and touchpads (sometimes integrated into the HMD helmets), some devices use finger tracking, either by gloves or by optical means. Six degree of freedom controllers are also common. Eye tracking is used in some devices, too.

7. Conclusions

Although extremely fast and promising development is taking place still a variety of problems exist which are already considered developers and researchers but are hard to tackle.

Still persistent issues are for example the Accommodation-Vergence Conflict [71], [72]. Huang et al. [73] have recently shown that it is in general possible to reduce this problem but their solution comes at the expense of resolution and frame rate.

User representation in HMDs is still sometimes problematic, as the game engine does not have enough information about the full posture of the user. In particular, users complain about seeing their hands and not being able to move them. Some advances are being made by the use of cameras, pose estimation etc. In some cases, the problem is sidestepped by using third-person view, so the user has a god-like, incorporeal view of the scene.

Another area, which is also challenging is the problem of Cybersickness. Unless latency is very low (in the order of a few ms), users will feel sick when they move their heads. Moving the users within the virtual world can also cause sickness, in a similar way to users in a car.

In the application area of architecture problems are underestimated like distance perception. Renner et al. provide a great overview on the different studies considering the wrong estimates of distance perception in virtual environments.

For research purposes the second wave of VR has brought a vast amount of upwind in the domain, HMD display technology has become affordable and improved significantly. In the domain of input devices the approaches seem promising. Displays for mobile devices are supposed to hit 11k resolution by 2018. While the eye cannot resolve such resolution for normal smartphone uses, in the case of VR applications the high-quality displays are required, as otherwise the extremely low eye-device distance and the magnifying optics make the pixels visible.

Besides the obvious advancements of bringing better-designed and more robust hardware as well as novel approaches in software and hardware, applications have been developed

Some issues on the hardware side, which are currently being addressed but will may need some time to obtain a solution, include: increase of resolution, improvement of optics and add per-user lens positioning capabilities. Becoming mobile will also improve current limitations with cables being tripping hazards and large computers limiting movement. Some improvements in mobile processors will be needed to be able to tackle the computational load needed, though.

Of course we are aware of the interesting developments on the other side of the MR continuum as for example the AR glasses Hololens and Magic Leap but we explicitly exclude them in the discussion.

It is the time to revisit Randy Pausch's iconic publication "Virtual Reality on Five Dollars a Day" [74] and use and play with the upcoming consumer hardware. We should take a look at the approaches coming from a differently biased community and combine the best of two worlds.

APPENDICES

A. OUTPUT DEVICE COMPARISON

	ResVert	ResHor	FOV	Tracking	Head	Eye	Touch	Vibration	Wind	Smell	Audio	Weight	Price	Available	
Cardboard				3	X								$10	X	https://www.google.com/get/cardboard/
VirtualVizor				3	X								$54	X	http://www.virtualvizor.com/
Wearality SKY			150	3	X								$49	X	http://wearality.com/
Samsung Gear VR V1			96	3	X		X							X	
Samsung Gear VR V2			96	3	X		X						$99	X	https://www.oculus.com/en-us/gear-vr/
Zeiss VROne			100	3	X								$129	X	http://vr-one.eu/
Gameface Mark V	2560	1440	140	X	X										http://www.gamefacelabs.com/
Auravisor	1920	1080	100	3	X						X		$260	P	http://www.auravisor.com/
HTC Vive	2160	1200	110	X	X										http://www.htcvr.com/
Oculus DK1	1280	800	110	3	X							380	$300	X	
Oculus DK2	1980	1080	100	X	X							440	$350	X	https://www.oculus.com/en-us/dk2/
Oculus - The Rift	2160	1200		X	X						X	380	$599	P	https://www.oculus.com/en-us/rift/
PlayStation VR	1920	1080	100	X	X										https://www.playstation.com/en-us/explore/project-morpheus/
FOVE	2560	1440	100	X	X	X						400			http://www.getfove.com/
HDK OSVR	1920	1080	100	X	X								$300	P	http://www.osvr.com/hardware.html
Sulon Cortex					X										http://sulontechnologies.com/
Avegant Glyph			45	X	X							450	$599	P	http://avegant.com/
VRVANA Totem					X										https://www.vrvana.com/
AntVR	1920	1080	100		X							370			http://www.antvr.com/
StarVR	5120	1440	210x180	X	X	X									http://www.starvr.com/
TeslaSuit								X							http://www.teslasuit.com/
Subpac M2								X					$399	X	http://thesubpac.com/
ARAIG								X			X				https://araig.com/
KOR-FX								X					$135	X	http://korfx.com/
VirWind									X						https://www.kickstarter.com/projects/699770549/virwind-virtual-reality-wind/
Feel Three								X							http://www.feelthree.com/
FeelReal									X	X			$299	P	http://feelreal.com/
Nirvana Mask				3	X				X	X	X		$799	P	http://feelreal.com/

Figure 13. An overview on the current output devices

B. INPUT DEVICE COMPARISON

	Tracking	Body	Head	Hand	Joysick	Touchpad	Vibration	Price	Available	
Grifta	X				X			$125	P	http://www.playgrifta.com/
SteamVR Controller	X				X	X				
Reactive Grip	X				X		X			http://tacticalhaptics.com/
Oculus Touch	X				X					https://www.oculus.com/en-us/rift/
Hydra	X				X				X	http://www.razerzone.com/de-de/gaming-controllers/razer-hydra-portal-2-bundle
Virtuix Omni								$699	P	http://www.virtuix.com/
Cyberith Virtualizer								$1249	P	http://cyberith.com/
WalkMouse										http://www.walkmouse.com/
WizDish								$556	X	http://www.wizdish.com/
Space WalkerVR								$4839	P	http://spacewalkervr.com
KAT WALK								$799	P	http://www.katvr.com/
Stompz										http://www.stompzvr.com/
Roto VR										http://www.rotovr.com/
VRGo										http://www.vrgochair.com/
InfinaDeck										http://www.infinadeck.com/
STEM	X		X					$299+	P	http://sixense.com/wireless
PrioVR		X						$1200	P	http://www.priovr.com/
Salto		X								http://salto3d.com/
Perception Neuron		X	X					$999+	P	https://neuronmocap.com/
ControllVR		X		X						http://controlvr.com/
Ximmerse	X	X		X	X					http://www.ximmerse.com/
LEAP Motion				X				$80	X	https://www.leapmotion.com/
Myo				X				$199	X	https://www.myo.com/
Gloveone				X				$211	P	http://www.neurodigital.es/
Manus				X					P	http://www.manusmachina.com/

Figure 14. An overview on the current input devices

C. Resources

Type	Name	URL	Language
Blogs	VR Times	http://thevrtimes.com/	ENG
	VR Times	http://www.virtualrealitytimes.com/	ENG
	VR Focus	http://vrfocus.com/	ENG
	VRWiki - a Wiki about VR	http://vrwiki.wikispaces.com/	ENG
	Road to VR	http://www.roadtovr.com/	ENG
	Virtual Reality Reviewer	http://www.virtualrealityreviewer.com/	ENG
	Upload	http://uploadvr.com/	ENG
	Doc-Ok	http://doc-ok.org/	ENG
	KZER0 Worldwide	http://www.kzero.co.uk/	ENG
	Austin Tate's Blog	http://blog.inf.ed.ac.uk/atate/	ENG
	Blog | Oculus	https://www.oculus.com/en-us/blog/	ENG
	Steam VR Blog	https://steamcommunity.com/steamvr	ENG
	OculusRift Blog	http://oculusrift-blog.com/	ENG
	oculusVRnews	http://www.oculusvrnews.com/	ENG
	Anomee	http://www.anomee.com/blog/	ENG
	VR Journal	http://vrjournal.com/	ENG
	VRR Virtual Reality Reporter	https://virtualrealityreporter.com/	ENG
	VR Nerds	http://www.vrnerds.de	GER
	VR Brillen	http://www.vrbrillen.net	GER
	Bloculus	http://www.bloculus.de/	GER
	VR Blog	http://vrblog.de/	GER
	Virtual Reality Systems	http://www.virtual-reality-systems.de/	GER
	3D Realms	http://www.3drealms.de/	GER
	Vrodo	https://vrodo.de	GER
	VR Blog	http://vr-blog.ch/	GER
Forums	Oculus Subreddit	http://www.reddit.com/r/oculus/	ENG
	Virtual Reality Subreddit	https://www.reddit.com/r/virtualreality	ENG
	Oculus Forum	https://forums.oculus.com/	ENG
	We are VR	http://vr.bosepark.com/	GER
Podcasts	Voices of VR	http://voicesofvr.com/	ENG
	EnterVR	http://entervr.net/	ENG
	Left-Handed VR	http://vrnews.tv/	ENG
	PodVR	http://www.podvr.com/	ENG
	Rev VR Podcast	http://www.revvrstudios.com/	ENG
	VRCasters	http://vrcasters.com/	ENG
	We are VR	http://vr.bosepark.com/	GER
	realo o virtual	http://www.realovirtual.com/es/rovcasts	SPN
Shop	OrangeCountryVR	http://orangecountyvr.com/	ENG
Events	VRLA	http://www.virtualrealityla.com/	USA
	SVVR	http://svvr.com/	USA
	VR Meetup	http://vr.meetup.com/	GLOBAL
	EuroVR	http://www.euvr.org/	EUR
	Oculus Connect	https://www.oculus.com/en-us/connect/	USA

Figure 15. **An overview on the online resources**

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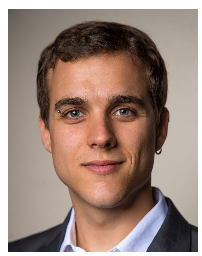

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