Hochschule
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Seminararbeit im Studiengang Game Engineering und Visual Computing

VR HARDWARE – ENTWICKLUNGS-GESCHICHTE, STAND DER TECHNIK UND AUSBLICK

Kurzbeschreibung

In den letzten Jahren hat sich Virtual Reality-Technologie in vielen verschiedenen Bereichen der Industrie etabliert, vor allem in der Unterhaltungsindustrie, aber auch in anderen Bereichen, wie etwa der Medizin und der industriellen Fertigung. Oftmals liegt hierbei der Fokus jedoch eher auf Seiten der Software, und viele Aspekte der Hardware werden vernachlässigt. Diese Seminararbeit gibt einen allgemeinen Überblick über die Hardware, die bei Virtual Reality Verwendung findet. Dabei liegt der Fokus der Arbeit vor allem auf der Entwicklungsgeschichte, dem aktuellen Stand der Technik und den Zukunftsaussichten der Technologie.

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1 INTRODUCTION

Over recent years virtual reality technology (VR) has gained more and more popularity, with consumer VR devices becoming ever more mainstream with every passing year. Nowadays, virtual reality finds application in a wide range of different fields and there has been an overall boom around the technology for several years. A reason for this is that, as Biocca et al. (1995) describe, the concept of virtual reality acts as a sort of gateway to the impossible, allowing for things to be done and exist that cannot exist in reality, with the limitation only really being the imagination (pp. 5-7). Especially in the area of entertainment virtual reality technology has found a strong foothold and virtual reality devices are being used for the consumption of many different media, like video games and movies. Virtual reality has also played an important part in the development of games that do not focus solely on the entertainment aspect, but instead provide a further meaning to the user through their gameplay. Examples for this are games designed to help support therapeutic approaches to deal with disorders and other medical conditions, as well as games designed to facilitate training of personnel and education. For instance, this can be done in the medical field (e.g., for surgeons), but also in fields like engineering and data visualization. One aspect of virtual reality that makes it such a good fit for these applications is that it offers an increased level of immersion compared to conventional media, since it is easier for the user to feel like they really are in, and part of, the virtual world.

Most people are already familiar with the term “Virtual Reality” at this point, though a major focus is often put on the software developments, and many people, particularly in the area of consumer VR, do not pay as much mind to the hardware involved in creating VR. This seminar paper tries to give a general overview of virtual reality hardware, with a special focus on answering the following questions:

- What is the origin of VR and its hardware?
- What developments have been made during its history?
- What is the current state of virtual reality hardware?
- What could the technology look like in the future?

The next section of this seminar paper aims to give a general idea about what virtual reality is and which hardware is used for different types of VR, as well as seeking to explain the basics of different tracking methods used with VR devices. The section after shines a light on the origin of virtual reality technology and what type of developments have been made for its hardware since then. Section 4 showcases a few popular VR devices that are being used nowadays and after that, in section 5, a short outlook on the potential future developments in the field of VR hardware is given.

2 BASICS OF VR AND VR-HARDWARE

The technology that is known as virtual reality today has not always been known by that specific name. The term “Virtual Reality” is often attributed to Jaron Lanier, a well-known and important figure in the history of VR technology, who popularized the term in the mid-to-late-1980s. (Yoh M., 2001, p. 667, Biocca et al., 1995, p. 4). Other names that have been used to describe the technology behind VR are *Virtual Environments*, *Artificial Reality* and *Cyberspace.* (McGreevy, 1991, p. 3).

2.1 DEFINING VIRTUAL REALITY

It is hard to define virtual reality unambiguously, even nowadays, when the technology has been firmly established in many fields. There are a plethora of different definitions that have been given by researchers who have tried to establish them for the technology, but most of them vary substantially from each other, especially when comparing early definitions to more current ones. It used to be quite common to define virtual reality based on the hardware that was used to create a virtual world at the time. Steuer (1992) gives several examples for these types of definitions, with all of them mentioning and tying virtual reality to particular hardware (like head-mounted displays and goggles, data suits and gloves) to some degree (pp. 74-75). Though these definitions are somewhat applicable to early versions of virtual reality, it is easy to see how definitions based on specific hardware aspects are hardly reasonable and accurate in combination with today's idea of virtual reality. Gigante (1993) defines virtual reality as the "illusion of participation in a synthetic environment rather than external observation of such an environment" (p. 3) and says that it "relies on three-dimensional (3D), stereoscopic, head-tracked displays, hand/body tracking and binaural sound" (p.3). While this definition does not base virtual reality on fixed hardware, it does constrain it relatively directly to the tracking of different body parts. Similarly, it can be argued that an identical issue can be found in the definition of Burdea & Coiffet, which base virtual reality on multiple human senses: "Virtual reality is a high-end user-computer interface that involves real-time simulation and interactions through multiple sensorial channels. These sensorial modalities are visual, auditory, tactile, smell, and taste". (Burdea & Coiffet, 2003, p.3).

Even though Gigante's as well as Burdea & Coiffet's definition are not wrong at all, it might be a better idea to define virtual reality more hardware agnostic, based on the different important "features" that are required for it. Such a definition is given by Sherman & Craig, who define virtual reality in accordance with its four key elements (Sherman & Craig, 2003, pp. 6-11):

- **A virtual world**, which they define as "an imaginary space often manifested through a medium" (p. 7) and "a description of a collection of objects in a space and the rules and relationships governing those objects" (p. 7).
- **Immersion:** The user has to be immersed in the experience. There are two different kinds of immersion that are at play here, one being *mental immersion*, and the other one being *physical immersion*. Mental immersion refers to the user feeling a kind of involvement in the experience, with phenomena like the suspension of disbelief (p. 9). This kind of immersion is offered by many different media other than virtual reality, while physical immersion is not, since it refers to the stimulation of human senses through technology, making the user feel as though they are *in* the experience (p. 9). Physical immersion is therefore a central part of virtual reality.
- **Sensory feedback:** This means that the user receives feedback of the virtual world through their senses. Usually this is visually through the display, but it can also be tied to other senses (p. 10).
- **Interactivity:** The user can interact with the virtual world in one way or another. This can range from being able to manipulate the virtual world directly by, for example, touching objects and the environment, or more indirectly, by being able to move in the virtual world, enabling the user to change their viewpoint.

Defining virtual reality based on these essential aspects of the technology guarantees that the use of most (if not all) hardware that can be used to achieve virtual reality coincides with a single definition. Build on these fundamental components Sherman and Craig construct the following definition (Sherman & Craig, 2003, p. 13):

> [Virtual reality is] a medium composed of interactive computer simulations that sense the participant's position and actions and replace or augment the feedback to one or more senses, giving the feeling of being mentally immersed or present in the simulation (a virtual world).

Using virtual reality technology over conventional media has a wide variety of advantages, which has led to the technology being used in all kinds of different fields. One of these advantages is that virtual reality can make an experience arguably more immersive, especially since the user can feel as though they are really physically *in* the experience. Cruz-Neira et al. (1993) mention one benefit of virtual reality over other media, namely that it provides more depth-cues: While conventional media provides depth-cues such as occlusion, perspective projection, atmospheric clues (e.g., fog), as well as lighting and shadows, virtual reality can add depth-clues such as binocular disparity, motion parallax and convergence. (Cruz-Neira et al., 1993, p. 135). Another advantage is given by Mandal who says that it can be used as an effective means of support for treatment in the medical field, for example for the treatment of phobias and disorders. (Mandal, 2013, p. 308). Simulating an environment and experience through virtual reality does not expose its user to any kind of immediate danger or potential physical harm. Two examples for this would be the treatment of arachnophobia, the fear of spiders, and acrophobia, the fear of heights, in virtual reality. (Mandal, 2013, p. 308). There is no risk of getting physically bitten by a virtual spider and the same goes for placing the user in an elevated position, they cannot fall. Of course, it is also an advantage that these virtual experiences can be paused or completely aborted at any time, simply by taking of the VR headset (or leaving a specific area if, for example, a CAVE is used). An additional benefit is that a main part of virtual reality experiences is purely software-based, which means that changes to the experience and new additions can be made without having to acquire new hardware that replaces the old one. It is obvious that the experience being completely virtual also means that the boundary of what can be displayed to the user is only limited by one’s imagination. This means that a wide array of experiences can be created that are designed to achieve different results. In a number of fields, but especially in the medical field, creating an environment for training of inexperienced personnel can mean a high cost or outright danger to the people involved. Virtual reality allows simulation of these environments and experiences without posing any direct danger and at a lower monetary cost than most alternatives.

Undoubtedly, there are also several disadvantages that come with the use of virtual reality. According to Mandal (2013), there is a concern that a VR environment could potentially affect the user psychologically and be more addictive (p. 308). They further explain this by giving the example of placing a user in a violent environment, which could in turn desensitize them to violence (p. 308). Furthermore, they mention that there is a concern of this creating a “generation of sociopaths” (p. 308). While this is an obvious exaggeration, it is reasonable to assume a virtual reality experience can affect the user psychologically (in both a positive, as well as a negative manner) and this could become a real issue once virtual reality (its hardware in particular) reaches the point where it is hard for the user to distinguish between the *real* reality and the virtual one. Another disadvantage is that the initial cost of the hardware required for virtual reality can be high. Virtual reality is oftentimes more resource intensive (Matthews et al., 2020, p. 400) and requires more powerful computer hardware to achieve high-end experiences. A VR experience can also regularly come with dizziness and cause nausea for the user, which is commonly referred to as motion-sickness or cybersickness. Furthermore, for many users, especially ones that are inexperienced with the technology, it might take some time to get accustomed to the virtual environment. Most people can walk around a room and grab objects with their hands just fine in real life, but once they are in the virtual world some people tend to struggle with these basic interactions. A lot of effort and thought has been put into relieving the user of such issues through smart design of the hardware that is used to interact with the virtual environment.

2.2 TYPES OF VR AND ITS HARDWARE

There are many different ways of categorizing virtual reality technology into different types, one of which is mentioned by both Mandal (2013) and Onyesolu & Eze (2011). According to them, virtual reality can be classified into non-immersive, semi-immersive and (fully-) immersive virtual reality, based on the level of immersion it provides the user with (Mandal, 2013, p. 307, Onyesolu & Eze, 2011, pp. 57-58):

- **Non-immersive VR:** This category makes use of standard computer monitors to supply the user with a view through a "window" into the virtual world, essentially using simple desktop computers, and interaction with the virtual world is purely done through use of common input-devices like mice and keyboards (Onyesolu & Eze, 2011, p. 57), while there are no other sensory outputs (Mandal, 2013, p. 307).
- **Semi-immersive VR:** Similar to non-immersive VR, semi-immersive VR uses normal computer monitors, but makes additional use of features like head-tracking and stereoscopic imagery to give the user a higher level of immersion and presence in the virtual environment (Mandal, 2013, p. 307, Onyesolu & Eze, 2011, pp. 57-58). It does not make use of any sensory output either (Mandal, 2013, p. 307).
- **Immersive VR:** Immersive VR, like the name suggests, immerses the user fully in the virtual reality experience. It uses head mounted-displays and similar technology, enabling the user to experience the virtual world with a fully stereoscopic view, which is based on the user's position and the direction they are facing (Mandal, 2013, p. 307, Onyesolu & Eze, 2011, p. 58). Systems in this category also make use of auditory, haptic, and other sensory feedback, with Mandal referring to this category as the "ultimate version of VR systems". (Mandal, 2013, p. 307).

While this way of classifying virtual reality allows for differentiation between types of VR based on how high their potential to immerse the user in the virtual world is, which by all means is a very important part of virtual reality in general, it does not allow for the wide variety of different hardware used to enable VR to be reflected accurately. Another way to group-up different kinds of virtual reality is by sorting the systems by what kind of method they use to visualize the virtual world to the user. This means that, in most cases, you can differentiate between different categories mainly based on the hardware that is used to visually display the virtual environment. There are five major visual display types (Sherman & Craig, 2003, p. 140):

- Fishtank VR
- Projection-based VR
- Occlusive head-based VR
- Nonocclusive head-based VR
- Handheld VR

The definition for Fishtank-VR is more or less the same as for the aforementioned semi-immersive VR. Sherman & Craig (2003) describe it as a computer monitor-based experience, that allows the user to look into the virtual world through a conventional monitor, much like looking through the glass of an aquarium, hence the name. (p. 140). The key difference to just interacting with a regular computer, and what makes this a type of virtual reality, is that the movement of the user's head is being tracked and the system alters the virtual scene accordingly (p. 141). The displays for this type of VR system can also be stereoscopic and tracking of the head is usually done through hardware like a video-camera (p. 141).

Projection-based VR systems use projection-surfaces surrounding the user to create the experience of being in the virtual environment. Multiple projectors are used to display the virtual scene on the screens around the user, which is usually achieved by having one projector for each screen, projecting from the rear of the surface in order to avoid throwing shadows inside the cube (p. 143). Sherman & Craig (2003) state that the user often has to wear a special pair of glasses to achieve stereopsis when looking at the displayed imagery and, of course, displaying a separate picture for each screen generally requires multiple computers that have to be synchronized (p. 145). Tracking of the user and their movement also requires a higher amount of information than with Fishtank-VR systems (p. 145).

While most people will usually associate head-based virtual reality with head mounted-displays, there are other specific types that are not directly mounted to the head of the user (p. 152). For example, the display device could be suspended on mechanical linkages and require the user to grab it with their hands (p. 152). Tracking of the user's movement using head-based VR can be achieved with many different tracking methods (p. 152). While there are a few disadvantages that come with this type of VR, there are also many benefits for the overall experience of the user (more on this in chapter 2.3). Sherman & Craig differentiate this category further into *occlusive* and *nonocclusive* head-based virtual reality. Occlusive in this case means that the VR device completely keeps the user from seeing the real world and instead the only thing the user can see is the virtual environment itself. As Sherman & Craig (2003) mention, a disadvantage of this is that everything, including the users themselves and objects like props, must be virtually displayed in one way or another (p. 154). Nonocclusive VR, on the other hand, passes through the real world to the user's view and lets them see their immediate environment, often using cameras, lenses or a setup containing mirrors to achieve this (p. 155). Nowadays this is often more associated with augmented reality than virtual reality.

Handheld virtual reality encompasses VR devices that can be held directly in the user's hands but still allow them to act as a window to the virtual world by tracking their movement and applying it to the view of the virtual space. (Sherman & Craig, 2003, p. 160). This is another kind of VR display hardware that is more commonly associated with augmented reality these days and is often used in the shape of smartphones and tablets.

Of course, sorting the different possible types of VR based on the hardware they use to visually display the virtual world allows for a more refined categorization of the technology, but it is also important to keep in mind that, as Sherman & Craig (2003) point out, the main aspect of virtual reality does not necessarily have to be entirely (or at all) a visual experience (p. 14). An example for this, that they mention, is a surgery simulator that only uses haptic feedback, which is transferred through the surgeon's hand to create a virtual reality experience, entirely forgoing the need for a primarily visual representation (p. 14). Even though there are virtual reality systems that do not use a visual representation at all, using a visual display of some kind is by far the most common way to achieve virtual reality currently. Therefore, the primary focus of the following chapters is the hardware used to visually display virtual reality, more specifically, head mounted-displays and the hardware that is used in conjunction with them.

Overall, the hardware devices used for virtual reality are commonly put into two main categories, namely *Input* and *Output* devices (Anthes et al., 2016, p. 3, Sherman & Craig, 2003, p. 14). Output devices resemble all the devices that provide the user with information about the virtual world, which is often done through visual, auditory, and haptic feedback (Sherman & Craig, 2003, p. 115), but are of course not limited to those senses. A few examples for output devices are displays (often head mounted-displays) that let the user see the virtual environment, speakers and headphones that transmit sounds of the virtual world to the user (Sherman & Craig, 2003, p. 164), and devices that give haptic feedback, like a controller that vibrates when a virtual object is being touched or a platform the user can stand on and that moves depending on the events in the virtual environment. Input devices, on the other hand, provide the user with a way to supply data to the virtual world, which can either be done actively or passively. (Mihelj et al., 2014, p. 53). An active input device would be a controller or props the user holds in their hands, and another example, which is mentioned by Anthes et al. (2016), are so called navigation devices. These devices can enable the user to ignore the limitations of the available space in the real world and walk without actually physically moving in any direction, essentially giving them an endless area to walk in in the virtual environment. (Anthes et al., 2016, p. 3). Passive input devices let the computer know where the user is located in 3D-Space and where they are looking (Sherman & Craig, 2003, p. 76), without the user actively giving this input. All the hardware and methods used to track the user's movement and orientation fall into this category.

2.3 HEAD MOUNTED-DISPLAYS

Head mounted-displays are by far the most popular and well-known visual display devices used to experience virtual reality, especially in the field of entertainment. They represent a hybrid category between input- and output-devices, as they typically not only display the virtual world to the user, but also track the movement of the wearer's head. When referring to head mounted-displays the abbreviation "HMD" is often used, but in combination with virtual reality they are also commonly described as VR headsets. They offer a higher amount of immersion to the user, which can be seen by the fact that they are usually used in fully-immersive VR applications and by Sherman & Craig (2003) describing them as a "natural, intuitive interface" (p. 14) for their users. Broadly speaking, they can be assigned into two different categories. (Anthes et al., 2016, p. 3).

The first of these two categories is wired HMDs. As the name implies, VR headsets in this category are tethered by one or more cables to an external computing unit, usually a powerful computer. (Anthes et al., 2016, p. 3). This has the advantage that they can use more capable hardware to compute the virtual environment and often means better overall performance for the different applications that are used on the device.

In the second category are mobile HMDs, which can be further split into devices that use casings in conjunction with smartphones and mobile HMDs that resemble a standalone system and are self-contained (Anthes et al., 2016, p. 5). According to Anthes et al., mobile HMDs often offer more limited options for interaction with the virtual world (Anthes et al., 2016, p. 5). Many of these devices, especially the ones that are smartphone-based, are often used only with very simple controllers, or are not used in combination with controllers at all. Not being wired to any external computer also means that these devices are tied to using low performing computing hardware (in comparison to their wired counterparts), though their in-built hardware still has the ability to provide an acceptable level of performance for most applications. Even with these downsides, Anthes et al. (2016) describe standalone mobile VR headsets as a "promising approach" (p. 3), which is a reasonable conclusion when looking at the advantages they provide to the user and for the virtual reality experience. For one, they are not tethered at all and are therefore not bound to any particular physical space, if the required tracking method allows it. This means they can be used almost anywhere and are very flexible in their transportation. Another benefit is that they often represent a cheaper alternative to wired HMDs, mainly because their components can be cheaper, and they do not require the purchase of an additional expensive computer.

In general, VR-HMDs often have several disadvantages and issues associated with them, a few of which are listed by Sherman & Craig (2003). Overall lag in display of the virtual world and tracking of the user can be a major issue and is a main reason for motion sickness (p. 152). The field of view in HMDs is often quite limited and in many cases the users are unable to wear the VR headset for prolonged periods of time due to eye strain, motion sickness and the encumbering nature of some devices (p. 153). Another drawback is that, in many cases, users cannot see their surroundings at all, which means that not only are interaction devices like controllers and keyboards with many buttons harder to use (p. 155), but there is also a greater risk of injury (p. 153) by bumping into objects and tripping over cables and furniture. While a digital representation of the boundaries for the safe area is often used to remedy this nowadays and can solve this issue to some degree, everything the user is supposed to see and interact with (e.g., their own hands, props, furniture, the entire virtual world) must be rendered and displayed in the virtual environment, which can be an issue for performance, might require additional tracking equipment and can also negatively affect the immersion of the user if the implementation is not good enough.

Sherman & Craig (2003) also mention several benefits that come with the use of head mounted-displays to display VR. For one, they isolate the user from the real world and are well suited for first-person experiences, because when the user looks into a specific direction, their view will automatically shift towards that direction as well (p. 153). Some HMDs also tend to cost less than other types of devices used for VR and they require less available room overall to setup (p. 164).

There are many factors that are at play and should be considered when evaluating any kind of VR headset, a few common ones, as well as the ones mentioned by Sherman & Craig and Burdea & Coiffet, are as follows (Sherman & Craig, 2003, p. 122, Burdea & Coiffet, 2003, pp. 60-61):

- Cost
- User comfort
- Mobility
- Portability
- Encumbrance
- Display
- Tracking system

While aspects like cost and comfort of the user are mostly self-explanatory, it might be harder to immediately understand what aspects such as mobility, portability and encumbrance entail. Mobility refers to how mobile an HMD is and how easily the user can move around physical space with it while it is worn. Two key questions that have to be answered for evaluation of this aspect are “Is the user tethered to any external computer?” and “What is the range of the tracking system?”, as the limitations based on cable length and tracking distance are factors for this. (Sherman & Craig, 2003, p. 136). Portability takes into account how easy the VR system is to transport to another location and how much effort it takes to set it up. (Sherman & Craig, 2003, p. 137). The amount of encumbrance a user experiences can be directly tied to an HMD being a wired or a mobile VR headset, with HMDs in general being more encumbering than other types of visual devices used for virtual reality. (Sherman & Craig, 2003, p. 138). Sub-factors that can be considered for judging encumbrance include whether or not cables are connecting the user to a computer, how much the HMD itself weights and how well it fits on the user’s head (e.g., for balance).

Displays play an extremely important role in the quality of an HMD-based virtual reality experience and how convincing the virtual world is for the user. There are many different depth cues that can be displayed using an HMD's screen, but two of the most important ones are depth cues based on stereopsis and motion, both of which rely heavily on parallax. (Sherman & Craig, 2003, pp. 119-120). Mihelj et al. (2014) define parallax as "the difference between an object's location in the image for the left eye and its location in the image for the right eye" (p. 118). Sherman & Craig (2003) also mention that while stereopsis-based depth cues are usually the most influential when in conflict with other kinds of depth cues, motion can be as strong or stronger (p. 120), and furthermore, bad stereopsis has the ability to cause discomfort in the user wearing the HMD (p. 125).

Even though there are multiple different types of displays that can be used in VR headsets (e.g., LCD (liquid crystal displays), CRT (cathode ray tubes) and OLED (Organic LED) to name a few) they all have attributes that they have in common and on which they can be evaluated on.

The resolution of a display gives information on the number of pixels along the screen's horizontal and vertical axes. Not only is an adequately high resolution important for the direct image quality, but the density at which the individual pixels are placed plays a critical role too, especially in HMDs where the distance between the user's eyes and the headset's screens is a lot lower by default. The smaller the distance between the eyes and displays is, the tighter placed the pixels must be to each other. (Mihelj et al., 2014, p. 115). This also means that smaller displays will look better to the user than bigger displays with the same number of pixels per area unit.

The term field-of-view (FOV) is used to describe the size of the area the user can see, usually in degrees vertically and horizontally (oftentimes only one value is given). According to Mihelj et al. (2014), the human field-of-view is around 200 degrees, with 120 degrees overlap in between the eyes (p. 115). They also point out that the amount of overlap is important, as too little overlap makes it hard to properly observe stereopsis (pp. 115-116).

Another attribute is the refresh-rate of the display, referring to how often the screen is updated per second, typically given in hertz (Hz) or frames per second (fps). The refresh-rate is a common unit of measurement for performance in computer graphics and a higher value usually means a better result, though the term framerate is more often used in this field, describing the number of pictures the computer can output per second for an application. In the field of VR, and particularly with HMDs, this plays a particularly important role, since a display's refresh-rate (or the framerate of an application that is being displayed by the HMD) that is too low can affect the user and their experience negatively, causing nausea or letting them perceive the displayed content as single images instead. (Sherman & Craig, 2003, p. 135).

The time it takes to update the displayed imagery on the headset's screens after changes to the position or orientation of the user have been made, known as latency, can also have a negative effect on the user's experience if it takes too long and should therefore be as small as possible. (Mihelj et al., 2014, p. 116).

While not necessarily being directly tied to the type of display being used, field-of-regard (FOR) is another characteristic that is of importance. Sherman & Craig (2003) define it as the "amount of space surrounding the user that is filled with the virtual world" (p. 129). As an example, the FOR in HMDs is oftentimes 100%, as the virtual world always covers the user's entire field-of-view and the headset moves in accordance with their head (p. 129).

Apart from these attributes, there are different effects that can affect the image quality of the displays. Even if someone is only vaguely familiar with virtual reality technologies they will probably have heard of the so-called screen-door effect. This effect refers to the tiny gaps that all the pixels of the screen have between each other, which means that a low pixel density magnifies how noticeable this effect is. This can have a substantial effect on the perceived image quality and is a major point that many of the current VR headsets try to address. While it is easier said than done, a relatively straightforward solution for this effect is an increase in the resolution of the display. (Anthes et al., 2016, p. 11). Other effects that have to be taken into consideration are persistence of the displayed images, which, when high, can lead to smearing of the seen image, and lens-effects, like distortions and shifting of colour values, called chromatic aberration. (Anthes et al., 2016, pp. 11-12).

2.4 TRACKING METHODS

Relaying the position and orientation of the user into the virtual environment with accuracy and believability is an integral part to creating a convincing virtual reality experience. For the user it is exceptionally easy to tell when something is off about the movements that are translated to the virtual world and when their idea of how the movement *should* look does not correspond with how it actually looks for them in VR. This means, that noticeable inaccuracy and overall lag in the tracking of their movements can lead to immediate uncomfortableness and motion sickness, as well as lessen the amount of immersion the user experiences. (Sherman & Craig, 2003, p. 78). Furthermore, this also means that accurate tracking of the user's general position and orientation is a particularly important aspect of virtual reality. In most VR experiences today, the position and orientation are based on the user's head, though individual body parts can also be tracked.

Virtual reality hardware, like head mounted-displays and controllers, can be tracked through the use of several different tracking methods, all of which require specific hardware components and have their own advantages and disadvantages. These tracking methods are part of the aforementioned input category of VR hardware. While it might be better to use a particular tracking method for specific use-cases and based on what the goal of the hardware is, there is no such thing as an ideal or perfect tracking system (Mihelj et al., 2014, p. 54), trade-offs must be made one way or another. According to Mihelj et al., the ideal tracking system would be small, self-contained, offer 6 degrees of freedom and be highly accurate (less than 1 mm and 0.1 degree tracking resolution), as well as offer fast tracking, be cheap, wireless, insensitive to occlusion and interference, and provide an infinite tracking range (Mihelj et al., 2014, pp. 54-55).

Common tracking methods used in conjunction with virtual reality devices are electromagnetic-, mechanical-, optical-, ultrasonic-, and inertial-tracking. (Burdea & Coiffet, 2003, p. 18, Mihelj et al., 2014, p. 55). All of these tracking methods are typically evaluated based on a number of general characteristics that are important for their tracking capability and that all of them have in common. One of the characteristics they are evaluated on is called degrees-of-freedom (DOF), which is supposed to give an idea of how much and what form of movement can be tracked. Sherman & Craig (2003) define a degree-of-freedom as “a particular way in which a body may move in space” (p. 80). Taking a look at a cartesian coordinate system, this means that there is one degree-of-freedom for the position along each axis and another one for the rotation that can be performed around each axis. In total there are three DOF for the translation and three DOF for the rotation that a tracked point in space can have. (Burdea & Coiffet, 2003, p. 17). Other attributes of tracking systems include their accuracy, which simply resembles by how much the reported tracking values differ from the real values that the tracked point should have, and what type of media can cause interference, or if there is any to begin with. (Sherman & Craig, 2003, p. 77). Additionally, latency, update rate, jitter and drift must be taken into account as well. The latency of a tracking system refers to the time it takes for the movement of a user to be registered by the tracking system, while the update rate is how often the tracking system updates the tracked points per second. (Burdea & Coiffet, 2003, pp. 20-21). Jitter is the change in the values that are reported by the system while the tracked point is not moving whatsoever, and drift describes the increase in tracking errors which accumulate over a certain period of time. (Burdea & Coiffet, 2003, p. 20). Most of the tracking methods mentioned above make use of two different hardware devices, a tracking device and a tracked device, which are referred to by different names, depending on the type of tracking system used.

Mechanical tracking:

Mechanical tracking was the first type of tracking to be used for virtual reality. (Burdea & Coiffet, 2003, p. 21). It is done through a mechanical construction, for example a mechanical arm, with multiple joints and linkages, that is suspended from the room's ceiling or a smaller device that is "worn" by the user and attached to the hardware the user utilizes for VR. (Sherman & Craig, 2003, pp. 79-81, Burdea & Coiffet, 2003, pp. 21-22). The values for the user's position and orientation can be derived from the angles of each of the device's joints. (Mihelj et al., 2014, p. 55). Tracking a device using this method has several advantages. It has a high accuracy and is fast (Mihelj et al., 2014, p. 57), in fact, Burdea & Coiffet state that this is the tracking method with the lowest latency compared to the other mentioned tracking methods. (Burdea & Coiffet, 2003, p. 22). Having a VR-Headset mounted on a mechanical arm can also take weight off the user and enables the potential use of force feedback. (Sherman & Craig, 2003, p. 80-81). Furthermore, mechanical tracking does not suffer from any kind of interference and occlusion is not an issue either. (Burdea & Coiffet, 2003, p. 22). On the other hand, having the HMD mounted to a mechanical construction not only limits the tracking range due to the fixed location of the tracking hardware, but can also be encumbering for the user and limit their overall mobility. (Burdea & Coiffet, 2003, p. 24).

Electromagnetic tracking:

This type of tracking uses a number of coils in combination with a magnetic field that is used to generate a current in the receiving device, which can in turn be used to determine the position and rotation of the tracked object. (Burdea & Coiffet, 2003, p. 24). The device that generates the magnetic field is called a source, while the receiving device is referred to as a sensor. (Mihelj et al., 2014, p. 72). The source is at a fixed location, which has to be known for calculations during the tracking. (Sherman & Craig, 2003, p. 78). While this tracking method does not need line-of-sight to the tracked device, interference in the tracking data due to ferromagnetic material can be a genuine issue (Mihelj et al., 2014, p. 73) and since the strength of the magnetic field decreases with distance, the tracking data is only accurate in a relatively close range to the source. (Sherman & Craig, 2003, p. 79). The hardware required for this type of tracking to work also makes it a "compact, light and relatively cheap" option, as Mihelj et al. (2014) state (p. 73).

Optical tracking:

The user can also be tracked through assessment of the environment using its visual data. Using devices like video cameras or other special optical devices (e.g. IR cameras), multiple kinds of markers can be tracked. (Mihelj et al., 2014, p. 59). This is done by analysing the location of the markers in the captured images through different computer vision algorithms. Optical tracking can also be done entirely without dedicated markers, but this means that more sophisticated algorithms have to be used.

These markers also act as reference points in the environment and can be referred to as "landmarks", which, of course, indicates that they are in a fixed location that must be known for the calculations. (Sherman & Craig, 2003, pp. 82-83). Markers can come in many shapes; they can range from small printouts with easy to recognize patterns and symbols on them to markers that are invisible to the naked eye. VR-Headsets often use a form of infra-red markers that are barely noticeable and can be easily incorporated into the device's design. As it has already been said, marker-less optical tracking is also an option. This is usually done by analysing the real environment and using distinctive shapes and points with high contrast as reference points. There are two general kinds of optical tracking that can be used in virtual reality (Rolland et al., 1999, p. 7-12, Welch et al., 2001, p. 4):

- **Inside-out:** The tracking hardware is on the device, while the markers are in a fixed location somewhere in the environment.
- **Outside-in:** The tracking hardware is in a fixed location somewhere in the environment, while the markers are on the tracked device.

Because new stationary markers can be added easily, inside-out offers a larger overall tracking area compared to outside-in (Burdea & Coiffet, 2003, p. 35), as well as better scalability and higher tracking resolution (Rolland et al., 1999, p. 13).

Since the images taken by the optical devices are only two dimensional, multiple devices are required for decent tracking information (Sherman & Craig, 2003, p. 82), and two separate devices are needed to be able to track the position and orientation properly (Mihelj et al., 2014, p. 65). Because this type of tracking is completely reliant on visual information, an obvious disadvantage is that a line of sight is always required in order to track a reference point. While this can be partially mitigated by using multiple reference points at once, as can be seen with most current VR-HMDs, it is a drawback nonetheless. In contrast to this, there are plenty of benefits. Not only does optical tracking allow for high update-rates, but it also has a low latency and allows for larger tracking areas in comparison to other tracking methods. (Burdea & Coiffet, 2003, p. 35).

Ultrasonic tracking:

Another tracking method is the tracking of a device via high frequency sound, using a transmitter at a fixed location in the room and a receiver on the device. (Burdea & Coiffet, 2003, pp. 32-33). The transmitter is essentially a speaker, while the receiver is a microphone, which means that the required hardware for this approach is fairly inexpensive. (Sherman & Craig, 2003, p. 84). This also means the required hardware is relatively compact (Rolland et al., 1999, p. 5) and Sherman & Craig (2003) say that the range of this tracking method can easily be extended by simply adding more speakers in the vicinity (p. 84). They also point out that in order to triangulate values for the positional and rotational state of the tracked device and achieve six degrees-of-freedom, multiple transmitters and receivers are required (p. 84). They also mention that this type of tracking can be quite encumbering due to cables and has an overall low range (p. 84). Since soundwaves are used to triangulate the position and orientation of the tracked device, this also means that the tracking relies on the speed of sound to work. This is another problem that is attached to ultrasonic tracking, because the speed of sound can vary and depends on environmental factors like temperature, pressure, and humidity. (Mihelj et al., 2014, p. 59). Another factor for this is an unobstructed view of the tracked object, because any type of object that is blocking the direct path to the receiver or even other soundwaves (environmental noise) can be reasons for worse tracking performance. (Burdea & Coiffet, 2003, p. 34).

Inertial tracking:
Inertial tracking makes use of devices like gyroscopes and accelerometers to determine the tracked object's relative position and orientation. The gyroscopes are used to deduce the change in orientation by measuring angular velocity and the accelerometers measure acceleration to discern the target's position. (Mihelj et al., 2014, p. 74). All of the required hardware is usually mounted directly to the tracked device, which has the benefit of this tracking method theoretically not having any limitations when it comes to tracking range, and furthermore, the hardware is relatively small which means it can easily be put into a self-contained package, while also being inexpensive. (Sherman & Craig, 2003, p. 86). Obviously, this type of tracking does not require any line of sight to the target like other tracking methods, all while offering quick measurements due to reduced latency. (Burdea & Coiffet, 2003, p. 39). The arguably greatest disadvantage is that, due to the measurements being relative instead of absolute measurements, tracking errors can quickly accumulate, which means that tracking based on inertia has a high amount of drift associated with it and leads to the tracking hardware regularly having to be re-calibrated based on a known orientational value. (Sherman & Craig, 2003, pp. 85-86).

2.5 OTHER INPUT- AND OUPUT-DEVICES

Apart from commonly used head mounted-displays and the hardware used for tracking them, there are a wide variety of other devices that can be used to provide the user with information about the virtual world and vice versa. Most of these devices usually target one or more human senses (or a specific aspect thereof), as more included senses oftentimes mean a higher level of immersion. (Sherman & Craig, 2003, p. 115). A few categories these input- and output-devices can fall into are the following:

- Devices used for interaction with the virtual world
- Devices used for navigation in the virtual environment
- Devices that stimulate specific human senses (Touch, Taste, Smell, etc.)

Interaction devices are devices like controllers, joysticks and gloves that allow the user to interact directly with the virtual world. A large percentage of the currently available HMDs include a pair of controllers that are included with the purchase of the device and the vast majority of current software applications, oftentimes (serious-) games, make use of these controllers as the main way of interacting with the virtual environment. Controllers have the significant advantage of already being a familiar tool of interaction for most users, as they heavily resemble conventional controllers used with videogame consoles, often having a similar physical button layout (e.g., joystick-like buttons for movement and trigger-buttons for shooting in first- and third-person shooters) and allowing for comparable mapping of each button's function. Of course, depending on the desired type of interaction more specific types of controllers can be used, or it might be an option to use standard console-controllers if the application allows it. For particular fields of application, a joystick or steering wheel can be a good alternative type of controller, for example if the VR-Application simulates driving of a vehicle, like a car, or flying a plane.

FIGURE 1: AN EXAMPLE FOR AN INPUT-DEVICE: ONE OF THE CONTROLLERS THAT ARE USED WITH THE HTC VIVE HMD.

Gloves that track the movements of the user's hand are another type of interaction device. While they are obviously one of the most natural feeling interaction devices for humans, gloves that are equipped with the hardware to track the movements of the user's hand can have the disadvantage of being hard to take off and put on, while also having to be calibrated to the hand of each new user before use. (Sherman & Craig, 2003, pp. 90-91). To make the virtual world more intuitive and realistic for the user, platforms and props can also be used. Oftentimes a platform is a scene that resembles the virtual environment constructed around the user (Sherman & Craig, 2003, p. 99), allowing them to physically interact with the virtual world (or rather, make them feel like they are interacting with it directly). Probs, on the other hand, are individual physical objects that can be touched by the user and are supposed to resemble virtual objects in the real world. Of course, both platforms and probs have the potential to give the user a higher immersion and increase realism through a sense of touch, which can make navigating and interacting with the virtual environment more intuitive (e.g., touching something in the virtual world overlaps with the user's sense of touch in the real world). They can also be used to achieve certain psychological effects, for which Sherman & Craig give a good example (Sherman & Craig, 2003, p. 98):

> Another benefit of props is that by making a specific object in the virtual world seem more real by giving it realistic haptic properties (such as a smooth or fuzzy surface), the rest of the virtual world may seem more real to the participant. This is called transference of object permanence [...]. A VR application for treating fear of spiders would offer an interesting example of transference: the user reaches out to touch a virtual spider, and they actually feel a fuzzy spider prop.

Navigation devices are hardware that help the user move in the virtual world. The virtual world is often many times bigger than the real physical space that is available to the user. While institutions and researchers might have rooms available that can fit small-scale virtual environments into them, normal consumers do not, and some virtual worlds can be larger than any room could ever reasonably be. There are plenty of solutions for this problem that allow the user to teleport around 3D-space with the push of a button or use thumb-sticks to move around on the software-side. VR applications can even employ clever design of the environment to keep the required physical space to a minimum, but this problem can also be solved through hardware alone. Iwata (2013) refers to such a navigation device as a locomotion interface, which "provides for the experience of physical walking while a walker's body is maintained localized in the real world" (p. 199). According to them, there are four main approaches to these types of hardware, which they describe as the following (Iwata H., 2013, p. 200):

- Sliding shoes: The walker wears specialized shoes that generate relative motion between the foot and the floor.
- Treadmill: The walker stands on a belt conveyer that moves opposite to the direction of walking.
- Foot-pad: Two platforms are applied to the feed and move in accordance with the motion of the feet.
- Robotic tiles: Movable tiles provides a dynamic platform for walking. The tiles move opposite to the direction of walking.

Apart from the devices used for navigating and directly interacting with the virtual world, there are other types of hardware that try to stimulate specific senses of the user. For example, such a device could try to emulate a particular taste or provide olfactory feedback to the nose of the user. Haptic feedback is naturally also a main target of research for this type of device. Many interaction devices already use very basic haptic feedback in the form of vibrations that are generated when the user interacts with a virtual object. Haptic feedback can also be integrated into hardware other than interaction devices, such as suits or vest. This type of haptic clothing can then be used to simulate events that happen in the virtual world, such as getting shot or punched by an NPC. Naturally, the haptic feedback does not necessarily have to be used only for extreme cases like these examples, environmental effects such as wind or rain also have the potential to be simulated.

3 HISTORY OF DEVELOPMENT

While a lot of people think virtual reality is a somewhat new technology because there is currently a massive technology boom around it (especially in the entertainment industry), that could not be further from the truth. The idea of virtual reality, as the kind of technology we know it today, has been around for the better half of a century in one way or another. If one were to count the basic ideas and concepts important for virtual reality technology and its hardware as the starting point in history for its development, then it could be argued that the origin of virtual reality as a technology lies a lot further back in time than that.

One such concept is stereoscopic imagery and the idea of stereopsis in general, which have been around for far longer. There have also been predecessors of virtual reality that have been purely mechanical in nature. (Berkman, 2018, p. 1). One such predecessor, that also makes use of stereoscopic imagery, is the so-called stereoscope. The stereoscope was invented in the middle of the 19th century by a professor from

England, called Charles Wheatstone. (Berkman, 2018, p. 2). It enables the user to experience the illusion of three-dimensions from a pair of two-dimensional images. (Kao et al., 2020, p. 134). A simple explanation of how this device worked is given by Berkman (2018), who says that the device had two separate mirrors that reflect two images (which are a bit different from each other) into the user's eyes (p. 2), though a more specific description can be found in Charles Wheatstone's book on his invention, titled "The stereoscope: its history, theory, and construction, with its application to the fine and useful arts and to education". (Wheatstone & Brewster, 1856).

The basic concept of virtual reality was also used in works of fiction as early as the 1930s. In 1934 a book with the title "Pygmalion's Spectacle" was published by Stanley Weinbaum, which used a concept that resembles virtual reality as one of its core plot-points. One of the characters that is part of the book describes the technology as the following (Weinbaum, (2012, originally released 1935), p. 4):

> […] a movie that gives one sight and sound. Suppose now I add taste, smell, even touch, if your interest is taken by the story. Suppose I make it so that you are in the story, you speak to the shadows, and the shadows reply, and instead of being on a screen, the story is all about you, and you are in it. Would that be to make real a dream?

The technology in the book allows the characters to experience a kind of interactive movie that stimulates multiple senses of the person using it, like sound, taste, and touch, to a highly realistic level through the use of a special pair of goggles. While the described technology is, even still, only possible in works of science-fiction, the idea behind the pair of goggles in the book resembles an ideal form of what virtual reality could be in the future.

Even though virtual reality as a basic theoretical concept was already around at this point, development on related hardware and overall virtual reality technology did not start until years later. The following section of this paper showcases a few of the major milestones in the development history of virtual reality technology and its hardware. This is obviously not a complete list of all the important breakthroughs and pivotal events, as there is simply to many. The importance of certain milestones can be argued as well and depends heavily on one's definition of what is important for virtual reality and what the correct definition of virtual reality itself is. While this list is roughly arranged chronologically, a few events have been grouped together to allow for easier readability.

3.1 EARLY DEVELOPMENT

Sensorama:
The Sensorama machine is often credited as the first step towards today's idea of virtual reality and was created in 1957 by Morton Heilig, though it was first shown publicly and patented in 1962. (Mandal, 2013, p. 304, Gigante, 1992, p. 5). Sensorama allows its user to experience a pre-recorded movie and provides stimulation of multiple senses throughout the movie. (Mandal, 2013, p. 304). The machine itself can be described as looking like an arcade machine with a booth that the participant would sit in and according to Robinett (1994) it was not only able to display stereoscopic imagery in colour, but also stimulate other human senses through binaural audio, simulation of smells, simulation of wind, and changes in temperature, and it provided haptic feedback in the shape of vibrations (p. 129). There have been five movies made by Morton Heilig that are compatible with the Sensorama machine (Robinett, 1994, p. 129), one of which displays a motorcycle ride through New York to the user (Gigante, 1992, p. 5). As Mandal (2013) points out, the Sensorama machine had all the

characteristics that can be said to make up a virtual reality system, except for the ability to interact with the virtual world, as the movies are entirely pre-recorded and do not allow for any kind of interactivity during playback (p. 304).

Telesphere Mask:
Morton Heilig also created a device with similar capabilities, the so-called Telesphere Mask, which he patented in 1960. The Telesphere Mask is regarded as one of the first head-mounted displays (Martirosov & Kopecek, 2017, p. 709, Kao et al., 2020, p. 134) and similar to Morton Heilig's other invention, the Telesphere Mask was able to display pre-recorded movies stereoscopically and provide the user with stereo audio (Martirosov & Kopecek, 2017, p. 709), but at the same time, had a form factor that allowed it to be easily worn on the user's head without being too encumbering. According to the invention's patent it is also able to simulate different temperatures, odours, and airflow. (Heilig, 1960). While the Telesphere Mask did not provide any kind of interactivity and could not track its user's head-position and orientation (Martirosov & Kopecek, 2017, p. 709), it did offer a relatively large horizontal and vertical field-of-view and was supposed to be able to completely block out light from the outside (Heilig, 1960).

The Ultimate Display:
In 1965, Ivan Sutherland, an American computer scientist, presented his concept of the perfect computer display in the paper "The Ultimate Display". In the paper, he lists some of the capabilities and limitations of computer displays and hardware at the time, and describes computer displays as a "looking-glass into the mathematical wonderland" that should stimulate as many human senses as possible (Sutherland, 1965, p. 506). Ivan Sutherland's idea of the ultimate display technology is described in the paper as the following (Sutherland, 1965, p. 507):

> The ultimate display would, of course, be a room within which the computer can control the existence of matter. A chair displayed in such a room would be good enough to sit in. Handcuffs displayed in such a room would be confining, and a bullet displayed in such a room would be fatal. With appropriate programming such a display could literally be the Wonderland into which Alice walked.

This can be more or less seen as the ideal vision of virtual reality, a perfect virtual reality created by a system that enables its user to interact with the virtual world, feel sensations such as touch, see, smell, taste, and hear their environment, all without being able to tell it apart from the real world.

3.2 VR DEVELOPMENT SINCE THE SIXTIES

Sword of Damocles:
Ivan Sutherland went on to develop one of the first head-mounted displays that was able to interact with a computer. (Kao et al., 2020, p. 135). He presented his work on this, at the time novel, device in his paper "A head-mounted three dimensional display" in 1968. As is seen in this paper, the device enabled the user to see the wire-frame model of a cube, projected into the room in front of them through usage of two miniature cathode ray tubes (p. 758). It was also able to track the head-position and orientation of the user through two sensors that used different tracking methods, one mechanical and the other one ultrasonic (pp. 760-761). The mechanical tracking sensor was a large, mechanical metal arm, which had to be mounted on the ceiling of the room and tracked the user's position and orientation through measurements at its joints (p. 760). The device was given the name "Sword of Damocles" by Ivan Sutherland because

of this mechanical arm. (Berkman, 2018, p. 4). The ultrasonic sensor was used as an alternative method of tracking to the mechanical one but had the issue of cumulative errors after a few minutes of use. (Sutherland, 1968, p. 763). Overall, the system was able to achieve a framerate of 30 frames per second (more precisely, it was able to draw 3000 lines at 30 fps) and had a field-of-view of 40 degrees. (Sutherland, 1968, pp. 758-759). Strictly speaking, the Sword of Damocles was an AR device, but due to the intertwined nature of both augmented reality and virtual reality, it is easy to see how it still resembles a major milestone in the development history of virtual reality and its hardware.

Artificial Reality (PSYCHIC SPACE, VIDEOPLACE):

In the year 1985, Myron W. Krueger and others presented multiple papers detailing their idea of *Artificial Reality* (Krueger, 1985, Krueger et al., 1985). He developed and prototyped a handful of systems to create responsive environments, in which the user and their actions can interact with a computer that responds with visual and auditory feedback in real-time. (Krueger, 1985, p. 145). Krueger started working on these responsive environments in 1969 (Krueger, 1985, p. 145) and two of the systems he created, that are especially relevant for virtual reality and positional tracking for virtual reality, are *PSYCHIC SPACE* and *VIDEOPLACE.*

The *PSYCHIC SPACE* system allowed tracking of the user's position and movement through hundreds of pressure sensors on the floor distributed throughout the room. (Krueger et al., 1985, p. 36). With these, game-like interactive virtual experiences were created, such as a maze that prevented cheating by extending its walls whenever the user tried to step over the two-dimensional boundaries. (Krueger et al., 1985, p. 36).

VIDEOPLACE was another responsive environment system that Myron Krueger developed and prototyped in 1974. (Krueger, 1985, p. 148). According to Krueger (1985), this system used a stationary video camera situated beneath the screen that was used as the output, to record the user's movements and project their silhouette into the virtual world generated by a computer (p. 147). Through the use of special hardware at the time (p. 147), the system was able to analyse the user's actions and body movements and let them interact with virtual objects and creatures in real-time (Krueger et al., 1985, p. 36), similar to today's interactions in VR and through devices like Microsoft's[1] Kinect. According to Krueger et al. (1985), only simple graphics have been used in the experience due to the computational cost and available computing power at the time (p. 37). They also mention several ideas for possible areas of application of this system, such as computer-aided instructions, telecommunication, and as an alternative input-method for computers (pp. 37-39). The experiences that were developed for this system were also kept intentionally game-like, as they saw games as an "extremely compelling interface" (p. 37).

Sayre Gloves:

In 1977 Thomas DeFanti and Daniel Sandin showcased their work on the Sayre Gloves, a device that uses the position of the user's fingers to generate input for a computer. The basic idea behind this input-device were flexible tubes that are placed on a glove along each finger of the user, each of which had a light source (e.g., an L.E.D.) on one end and a photocell (e.g., a Phototransistor) on the other end. As DeFanti & Sandin (1977) describe in their report, when the user moves their fingers, the tube begins to bend and compress, which leads to less light being able to hit the photocell (p. 6). By measuring the amount of light that arrives at the end of the tube, the position of the

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[1] Microsoft Corporation - https://www.microsoft.com

fingers can be estimated. While there were a handful of minor issues with the Sayre Gloves (p. 6-7), according to DeFanti & Sandin, a Sayre Glove "is easy to build and fits many hand sizes" (pp. 5-6) and they also found the resulting computer input of the gloves to be very smooth and have a low amount of noise (p. 7).

VPL - Jaron Lanier:

Jaron Lanier, a major contributing figure in the field of early virtual reality, founded the company VPL Research (VPL = Virtual Programming Lab) in the late 1980s. (Martirosov & Kopecek, 2017, p. 709). The company's original goal was to develop virtual programming languages, though they shifted their focus on developing virtual reality hardware technologies (Sherman & Craig, 2003, p. 30) and were one of the first companies to sell virtual reality-related products commercially (Burdea & Coiffet, 2003, p. 8). VPL is responsible for developing one of the earliest examples of VR input hardware in the form of a glove, the DataGlove (Burdea & Coiffet, 2003, p.8), and they also developed the EyePhone (Sherman & Craig, 2003, p.30).

Similar to DeFanti & Sandin's Sayre Gloves, the DataGloves were able to measure the amount of bending each of the user's fingers is experiencing, which was achieved by using fiber-optic sensors and lets the user interact with a computer through the use of gestures. (Burdea & Coiffet, 2003, p. 8). The majority of DataGlove models had 10 different sensors, two allocated to each finger, and used a form of magnetic tracking to determine the position and orientation of the user's hand. (Sturman & Zeltzer, 1994, p. 32-33). According to Burdea & Coiffet (2003), a few of the issues that the DataGlove had were that it was not affordable, did not provide the user with tactile feedback and had difficulty being adjusted to different hand sizes (p. 8). Sturman & Zeltzer (1994) also mention that it was not accurate enough for complex gesture input and only had an update-rate of around 30 Hz, which is not a high enough update-rate for specific use-cases (p. 33).

In their book, that was published in 2003, Burdea & Coiffet describe VPL's EyePhones as virtual reality head-mounted displays that present stereo images to the user through LCD displays, which displayed the imagery blurred as they had a low resolution of 360 x 240 pixels (p. 9). They also point out that these HMDs were quite expensive at the time and comparatively heavy, costing 11000 US-Dollars and weighing over two kilograms (p. 9).

NASA – Project VIVED/VIEW:

A major contributor to virtual reality technology in the late 20th century was NASA[2] (National Aeronautics and Space Administration), which produced considerable milestones in the area of virtual reality hard- and software during this time. (Kao et al., 2020, p. 135). Burdea & Coiffet (2003) state that in 1981 researchers at NASA created the prototype of a head-mounted display that used LCD screens in conjunction with special optics (p. 7). This HMD, or rather, the project this HMD was used in, was titled VIVED (Virtual Visual Environment Display) and was later build upon by Scott Fisher, who integrated a special version of VPL's DataGlove (p. 7). Later on, the VIVED project progressed into the VIEW project, which stands for Virtual Interface Environment Workstation (p. 8).

As Fischer et al. mention in their paper in 1987, the head-mounted displays used in both these projects were only able to display stereoscopic imagery in a single colour and had a field-of-view of 120 degrees vertically and horizontally for each eye, with a binocular field-of-view of 90 degrees (p. 78). They describe the integrated LCD displays

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[2] National Aeronautics and Space Administration - https://www.nasa.gov/

as having a medium resolution and point out that the HMD was able to track the position and orientation of the user's head in real-time and with 6 DOF (p. 78). In addition, this VR system also made use of speech recognition and gesture input, which was achieved through the aforementioned DataGlove that allowed tracking of the user's hand and fingers (p. 80).

The main goal of this research at NASA, according to Fischer et al. (1987), was to "develop a multipurpose, multimodal operator interface to facilitate natural interaction with complex operational tasks and to augment operator situational awareness of large-scale autonomous and semi-autonomous integrated systems" (p. 77). The primary fields of application planned for the projects were telerobotic/telepresence, information management and human factors research (pp. 83-85). At the end of their paper, they discuss their research results on the VIVED project by comparing it to other virtual reality/virtual environment displays at the time (Fischer et al., 1987, p. 85):

> The described system is portable and low-cost without large space and equipment requirements. In comparison to other research efforts in head-mounted displays, this system is unique in presenting a stereoscopic image that closely matches human binocular vision capabilities and in its configuration with state-of-the-art speech and tactile input technology.

Additionally, both Fischer et al. (1987) and McGreevy (1991) predicted usage of virtual reality technology, like it has been developed in their research at NASA, in further areas of application, such as (Fischer et al., 1987, p. 86, McGreevy, 1991, p. 4):

- Education
- Computer-aided design and simulation
- Scientific visualization
- Entertainment
- The medical field

With the widespread use of virtual reality technology in all of these fields and many additional ones today, it's easy to see that these predictions were correct.

Flight simulators and the military:

Flight simulators and the US-Military/Department of Defense[3] played an important role in the history of virtual reality. While flight simulators are responsible for crucial development of the technology and helped in finding the basic requirements needed for virtual reality (Gigante, 1992, pp. 5-6), the department of defense funded early virtual reality technology and virtual reality related research (U.S. Congress, Office of Technology Assessment, 1994, p. 2).

One flight simulator that was used and funded by the military was VCASS (Virtually Coupled Airborne System Simulator). As Gigante (1992) states, this system was developed by Thomas Furness in 1982 (p. 5). Like many of the previous systems in the field of virtual reality, VCASS made use of a head-mounted display and enhanced the wearer's view with graphical elements in the form of an overlay (p. 5). The overlay was able to present information, such as targeting and threat information, friend-or-foe identification, and displaying information regarding the flight path (p. 5). In a report from the Office of Technology Assessment of the U.S. Congress (1994) it is mentioned that the HMD used a magnetic tracking method to track the position and orientation of the user and displayed the graphical elements through monochrome cathode-ray tubes

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[3] U.S. Department of Defense - https://www.defense.gov/

(p. 7). The report also states that the VCASS system provided a high amount of visual detail, even compared to newer technology at the time (p. 7).

Later, the VCASS system was further developed and used in the super cockpit program (p. 7). The new version of the system also provided three-dimensional sound and tactile interaction, as well as using not only the head and hands as inputs, but also the speech and eyes of the user. (Furness, 1986, p. 48). The super cockpit was able to display and visualize almost all instruments of the cockpit to the user in the virtually generated environment, including navigational data like flight direction and waypoints, information on and simulation of onboard weapon systems, as well as several switches. (Furness, 1986, pp. 49-51). Like the previous iteration, it used magnetic tracking to gather positional and orientational data with six degrees-of-freedom for the head and hands of the user, as well as having a field-of-view of 140 degrees horizontally and 60 degrees vertically. (Furness, 1986, pp. 49-50).

CAVE:

The CAVE-System represents an alternative way of displaying the virtual environment for virtual reality. The name CAVE stands for “CAVE Automatic Virtual Environment” and the system was developed around the beginning of the 1990s, premiering publicly at SIGGRAPH in 1992. (Cruz-Neira et al., 1993, p. 135). The researchers behind the CAVE-system explain its concept, advantages, shortcomings, design, and practical application in great detail in their two separate papers (Cruz-Neira et al., 1992, Cruz-Neira et al., 1993). A short and very simple description is given by Cruz-Neira et al. (1992), stating that the CAVE system is essentially “a cube with display-screen faces surrounding the viewer” (p. 67). The system is made up of a number of projection screens facing the user and surrounding him, each of which receives a projection of the virtual environment from the outside (Cruz-Neira et al., 1993, p. 136), creating the effect of the user being in the virtual world.

While in concept a CAVE-system can have six individual projection screens, one for each direction, in practice at SIGGRAPH 1992 it had only four, one in the front, one each for the left and right sides and one for the floor. (Cruz-Neira et al., 1993, p. 136). The first CAVE-like system using all six directions wasn’t available until 1998. (Sherman & Craig, 2003, p. 35). Cruz-Neira et al. (1993) explain in their paper, that in order to track the position and rotation of the user’s head, and let the user experience a three-dimensional effect, a pair of stereo glasses had to be worn, which were equipped with shutters and had the tracking system mounted on the top (pp. 136-137). This tracking system made use of a magnetic method (p. 136) and offered six degrees-of-freedom to the user (p. 138). The hands of the users were also tracked using this method (p. 136). The imagery that was projected onto the screens from the outside had a resolution of 1280 x 1024 pixels and was updated at 60 Hz (p. 138). Overall, the CAVE system that was presented to the public took up a space roughly 3 x 3 x 3 meters and due to the use of magnetic tracking, some special construction measures had to be taken (p. 136). To facilitate rendering of the virtual environment, the system required five separate high-end workstations, one for each projection and another one for communication with input devices and overall synchronisation (p. 136).

Cruz-Neira et al. (1993) also state that the CAVE-system was developed with researchers in mind, wanting to deliver minimal encumbrance and attachments (p. 136), and they described the overall motivation to be “to create a VR display that is good enough to get scientists to get up from their chairs, out of their offices, over to another building, perhaps even to travel to another institution” (p. 136). Some of the goals they wanted to achieve with the CAVE are a higher image quality, a system that is less susceptible to errors and the ability to take real devices into the virtual world (p. 136). In terms of display resolution and colour the projection-based system was able to match conventional display methods (p. 135) and provided the user with a large field-of-view. Further advantages they mention include a lower distortion compared to other VR systems, as well as less sensitivity to tracking errors (p. 141) and only a fraction of users experienced severe motion sickness (p. 138). Of course, there were some drawbacks and unsolved issues as well, such as the high cost of the system, the user's hand as well as other objects and people between the user and the screens being able to break the illusion, the hardware being relatively sensitive and fragile, which therefore makes it hard to deploy in specific settings, and the fact that users still had to be tethered (p. 141).

Rise of VR for consumers:
Up till this point, VR was mostly available as a somewhat novel means of (scientific) research in a variety of fields, but during the 1990s virtual reality technology and hardware became increasingly available for the consumer market. According to Kao et al. (2020), a lot of companies were hurriedly trying to achieve monetary gain from the hype around the technology at the time (p. 135). A few of these companies were industry giants like Sega[4], Nintendo[5] and Disney[6], which all put large amounts of money towards the widespread adoption of virtual reality technology (p. 135). Kao et al. (2020) go as far as calling this the "first golden age of VR" (p. 135). On the contrary, even though large amounts of money and time were put towards achieving widespread adoption of virtual reality technology, most of the abovementioned companies experienced "only failure after failure" (p. 136).

- **Sega** announced a promising virtual reality-headset for its line-up of video game consoles during this time, yet, because of tests showing issues that made the users feel uncomfortable, like motion sickness and headaches, it got cancelled before it launched (p. 136).
- **Nintendo** released its VR-console/HMD titled "Virtual Boy" in 1995 to disappointing sales numbers (p. 136). Kao et al. (2020) attributes the failure of the console to "high prices and unimpressive technology such as lack of portability, a monochrome display, and an unimpressive 3D effect" (p. 136).
- **Disney** opened up a number of theme park-attractions that included VR in the shape of HMD- and projection-based systems (Sherman & Craig, 2003, p. 35), but one of them got shut down only two years after the initial opening, with none of them still open as of today (Kao et al., 2020, pp. 135-136).
- **Virtuality** was the name of another VR system during this time, which was developed by W-Industries[7] and was an arcade-style VR setup that enabled two players to play in a multiplayer-environment. (Sherman & Craig, 2003, pp. 31-32). Two versions of this system were developed, one offering a standing and the other one a seated experience. (Gigante, 1992, p. 13). The first application available for the Virtuality-VR-System was a basic player-versus-player shooter (Sherman & Craig, 2003, pp. 31-32), though at least at first, only W-Industries was able to write applications for the system (Gigante, 1992, p. 13).

Kao et al. mention multiple possible reasons and explanations for these failures, namely the form-factors of head-mounted displays, unavailability of computer hardware that was powerful enough, and lack of adequate display resolution at the time. (Kao et al., 2020, p. 136). Other reasons were that "public expectations were

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[4] Sega Corporation - https://www.sega.com/

[5] Nintendo Co., Ltd. - https://www.nintendo.com/

[6] The Walt Disney Company - https://thewaltdisneycompany.com/

[7] Virtuality Inc., (formerly W-Industries) - https://virtuality.com/

unrealistically high due to sustained media hype", as Burdea & Coiffet (2003) mention (p. 10), and additionally, of course, that the overall cost of hardware related to the technology during this time was high (Gigante, 1992, p. 12). This eventually led to financial resources drying up (Burdea & Coiffet, 2003, p. 10) and the end of "the first true rise of VR" at the start of the new century, as Kao et al. (2020) put it (p. 136).

Contrary to this, Burdea & Coiffet (2003) actually state that virtual reality underwent a "rebirth" in the late 90s (p. 10). They credit increased performance power of computers, lower cost of the technology and advancements in display technology for this (pp. 10-11) and say that LCD-based HMD displays presented a cheaper alternative to CRT-displays and became available with acceptable resolution: 640 x 480 pixels in 1997, with 1024 x 768 pixels a short amount of time later (p. 11). Similar reasons are given by Mazuryk & Gervautz (1996), with them stating that a lower price point and higher computing performance "finally brought VR to the masses" (p. 12).

4 CURRENT STATE OF DEVELOPMENT

Nowadays virtual reality is a common technology to be used in many different areas of application, it plays a major part in the medical field and training of personnel. According to Anthes et al. (2016), today's virtual reality technology and hardware "are already precise and robust enough to be used for professional operation and scientific experiments" (p. 1). Even though VR is used in a wide variety of fields and plays an important part in many industries (Gausemeier et al., 2011, p. 7), the area of entertainment is the one in which VR currently finds the most usage by far. The focus on entertainment applications does not mean that progress is not made at all in scientific developments, in fact, development in the area of entertainment is of benefit for the scientific community, mainly because it comes with an increased interest in the technology and more money being put into developing the hardware, not only improving the resulting devices but also making it more affordable in the process. (Anthes et al., 2016, pp. 1-2).

The current wide-spread adoption of the technology and overall boom around virtual reality as a whole has started around 2010 and has been referenced by Anthes et al. (2016) as the "second wave" of virtual reality (p. 1). Taking a look at the hardware and devices that have been developed since the start of this boom, it is obvious that the present focus of research and development of the technology lies heavily on head mounted-displays as the main hardware used to display virtual reality, which is reinforced by Anthes et al. (2016) saying that other types of VR are lacking relevancy in today's developments (p. 3). They go further and say that a similar thing applies to once common tracking methods, like mechanical-, electromagnetic- and ultrasonic-tracking (p. 12), as today they are simply not relevant anymore for the vast majority of HMDs. Instead, they state that the currently most used tracking method is optical tracking, more specifically, optical tracking using infra-red diodes, and the present focus of development of tracking lies with reduced tracking latency and fusion of multiple sensors (p. 12). An excellent example for this is that most modern VR-HMDs utilize technology normally used in inertial tracking, namely accelerometers, magnetometers, and gyroscopes, in combination with the optical information to track the position and orientation (p. 5).

In addition to this, the display technology used in head mounted-displays has massively improved, which is mainly thanks to developments and progress in the smartphone industry. (Faisal, 2017, p. 298, Anthes et al., 2016, p. 10). Cathode ray tubes, which once have been a common type of display in virtual reality devices, are no longer used in the majority of current HMDs, instead LCD and OLED technology is often found in the displays of these devices. LCD-Screens usually have high persistence associated with them, while OLED-Screens are low persistence. (Anthes et al., 2016, p. 11). In their 2016 paper, Anthes et al. say that the displays of "latest-generation HMD use a persistence no longer than 3 ms for 1k x 1k resolution with a 110° FOV" (p. 11). While these specifications are a couple years old now, it is safe to assume that today's generation of HMDs has specifications that are at least the same or even better on average. This is proven by the specific examples of current HMDs showcased later in this chapter.

As already stated, virtual reality and its hardware currently find the biggest utilization in the field of entertainment, more specifically, in the gaming industry. (Kao et al., 2020, p. 137). Many of the companies who are developing the current VR headsets are also deeply involved in the gaming industry, the best example for this is the Valve Corporation[8], commonly referred to simply as Valve. Valve is an American company that, on one hand, is the developer of the Valve Index, which is currently one of the state-of-the-art consumer VR-HMDs, while on the other hand, it is the company behind Steam[9], arguably the biggest gaming platform and distributer of videogames on PC. In a recent monthly hardware survey on Steam from April 2021[10], Valve inquired steam users about if, and which, VR headsets they are using, with the results being that 2.22% of steam users possess some kind of virtual reality device. The five most used headsets according to this survey are the Oculus Quest 2 (27.79%), Oculus Rift S (20.25%), Valve Index (16.39%), HTC Vive (11.38%) and the original Oculus Rift (6.29%). Both the Oculus Rift and HTC Vive are devices from the first generation of current VR headsets, while the Valve Index and Oculus Quest 2 represent state-of-the-art consumer VR hardware. Since these devices are mostly made by companies and are being sold commercially, many of the details and information regarding the hardware are only available on the manufacturer's websites, blog posts, and, especially in the case of the HTC Vive and Valve Index, through presentations and talks at conferences and conventions.

4.1 OCULUS RIFT AND HTC VIVE

As previously mentioned, the current interest in virtual reality started around 2010 and is mainly thanks to a company called Oculus[11], which has since been acquired by Facebook[12]. In 2012 Oculus set up a kickstarter campaign to fund development of the VR-HMD that started the current VR boom, the Oculus Rift. During its development multiple development versions were released, which are referred to as development kits (e.g., Oculus Rift DK1 and DK2), with the final consumer version releasing in 2016 (referred to as CV1) at a price around 600$ at the time.

The earlier version had issues with persistence, which Anthes et al. (2016) attributes to "LCD display technology, where pixels under constant illumination lead to a perceptible smearing during rotation" (p. 11). One of the last developmental versions,

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[8] Valve Corporation - https://www.valvesoftware.com/

[9] Steam - https://store.steampowered.com/

[10] Steam Hardware Survey (April 2021) - https://store.steampowered.com/hwsurvey/Steam-Hardware-Software-Survey

[11] Oculus - Facebook, Inc. - https://www.oculus.com/

[12] Facebook, Inc.

the Oculus Rift DK2, had very similar specifications to the final version. According to Desai et al. (2014), it offered an OLED display setup with 960 x 1080 pixels per eye and a pixels per inch (PPI) value of 441, with the display being capable of displaying a refresh rate of 75 Hz and the headset having a horizontal FOV of 90 degrees (p. 176). with the DK2 version was as low as 2 ms and the headset itself weight around 440 g (p. 176). In comparison to this, the final version of the Oculus Rift improves a few of these specs. As mentioned on the device specification website of Oculus, it does not only offer a higher resolution of 1080 x 1200 pixels per eye and a higher display refresh rate of 90Hz (Facebook Technologies, LLC. [4]), but it also offers a slightly bigger field of view (Borrego et al., 2018, p. 152). The Rift's controllers, called the Oculus Touch or Half Moon due to their shape, have multiple buttons and support basic gesture recognition, based on which finger is in contact with the device (Anthes et al., 2016, p. 7), as well as simple haptic feedback through vibrations. The controllers also have a loop that encases the user's hands while holding the controller, which has multiple markers on it and is used for optical tracking. (Anthes et al., 2016, p. 7). Both the Oculus Rift headset and its controllers are being tracked using optical tracking of IR-LEDs, more specifically outside-in tracking with 6 DOF. In addition to two or more cameras that must be placed at suitable locations in the room, the Oculus Rift also makes use of inertial tracking through gyroscopes, magnetometers, and accelerometers. (Desai et al., 2014, p. 177). The update rate of the tracking can be up to 1 kHz (Desai et al., 2014, p. 177) and its accuracy, according to Anthes et al. (2016), is around 1 mm or 0.25 degrees (p. 12). Additionally, in their tests Borrego et al. (2018) found that a tracked area of 11.75 m^2 is possible (p. 154).

Around the same time as the consumer version of the Oculus Rift, another VR-HMD called the HTC Vive was released, though the headset was being prototyped as early as 2014 (Valve Corporation [2]). This headset was developed by HTC[13] in cooperation with the aforementioned Valve Corporation and offers very similar specifications to the Oculus Rift, at a price point that is slightly higher than the Rift's at around 800$. It uses two AMOLED displays with a resolution of 1080 x 1200 pixels each, equalling a combined resolution of 2160 x 1200 pixels, and while the display refresh rate is the same as the Rift's, with the pixel density also being very similar, it offers a bigger FOV with 110 degrees (HTC Corporation [1]), though it is a good bit heavier than the Rift with a weight of 563 g (Borrego et al., 2018, p. 152). Compared to the Oculus Touch controllers, the Vive controllers do not offer gesture tracking, but come equipped with a touch pad that can be used for precise actions in many applications and they offer basic haptic feedback through vibrations. Similar to the Oculus Rift, the HTC Vive also makes use of inertial tracking in addition to optical tracking, but the way the optical tracking works is quite different.

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[13] HTC Corporation - https://www.htc.com

FIGURE 2: THE HTC VIVE, A VIRTUAL REALITY HEAD MOUNTED-DISPLAY.

The Vive uses SteamVR tracking technology, which is based around a set of base stations mounted in the environment. These base stations are also referred to as Lighthouses due to the way the tracking method works. In a talk at the Steam Dev Days[14], Ben Jackson[15], an employee at Valve, briefly explains the tracking method (3:30-7:38): Each base station houses an array of IR-LEDs and two individual rotors. The rotors produce an IR-Laser that sweeps through the room, with one rotor sweeping horizontally and the other one sweeping vertically. Before the sweeps can begin, the array of LEDs will flash brightly to synchronize all devices. The headset and controllers all have many sensors on them that notice when they are being hit with IR-Light, which means that the position and orientation of the devices can be calculated based on the time it takes for the lasers to hit each sensor.

While this tracking method might seem like optical outside-in tracking at first, it is indeed inside-out tracking, because the headset itself is responsible for positional and orientational tracking, while the base stations only act as (very advanced) reference points. Due to using SteamVR tracking technology, the tracking itself has an update rate between 250 Hz and 1 kHz (Valve Corporation [2]) and the recommended maximum tracking area is 3.5 m x 3.5 m, but a tracking area of 24.87 m^2 is possible (Borrego et al., 2018, p. 154). The tracking overall has a low latency of less than 10 ms (Anthes et al., 2016, p. 12) and provides sub-millimeter accuracy when tracking

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[14] Steam Dev Days - https://steamcommunity.com/devdays

[15] Presentation of Ben Jackson on Valve's Steamworks Development Youtube-Channel, published online on 29.11.2016 - https://www.youtube.com/watch?v=BhzUn0gmkEU

stationary devices, with tracking becoming less stable when moving (Borges et al., 2018, pp. 2611-2612). Niehorster et al. (2017) conducted a study on the viability of the HTC Vive's tracking in scientific research and found that, while end-to-end system latency and a low noise level were in favour of viability, the tracking has a tendency to deliver incorrect measurements for both roll and pitch rotational values, as well as experiencing a change in orientation whenever the device loses tracking (pp. 19-20). They state that this makes the HTC Vive not suited for research that requires high accuracy when it comes to those measurements, but it can be a good option when accurate measurements are not a requirement (p. 20).

FIGURE 3: ONE OF THE BASE STATIONS THAT ARE USED FOR TRACKING THE HTC VIVE AND ITS CONTROLLERS.

4.2 VALVE INDEX AND OCULUS QUEST 2

While the Valve Index has been released around two years ago, in 2019, it is still one of the best and most popular VR headsets around, even though with a price tag of around 1300$ (including a pair of controllers and two base stations) it is almost twice as expensive as other HMDs and was somewhat hard to come by when it initially released. According to the headset's website, it uses two inbuild LCD screens with a resolution of 1440 x 1600 pixels each, offering a very low persistence of 0.330-0.530 ms, which is a five-times improvement over first-generation devices like the HTC Vive and Oculus Rift. The website also states that the displays are updated at 120 Hz (though they also support 90 Hz and 144 Hz refresh-rates) and the headset provides the user with a field-of-view of 130 degrees. (Valve Corporation [3]).

The controllers that the Valve Index uses also offer an array of new features compared to older controllers. They have a strap that the user can fasten around their hand, allowing them to use the controller without having to hold it directly. This is used in combination with tracking of the individual fingers to allow for more natural interaction with the virtual world. Valve states on the controller's website that each of the controllers has 87 sensors to track hand and finger positions, as well as motion and pressure values to determine the intent of the user. (Valve Corporation [4]). Apart from this, the controllers also offer a wide variety of other input options, such as buttons and triggers, and they can provide the user with haptic feedback through vibrations.

The tracking system is very similar to the tracking system of the HTC Vive, but the Index uses a newer version of the base stations and of SteamVR tracking. This means that the tracking system of the Valve Index offers an increased tracking range (a 400% larger area than the Vive's tracking system, according to Valve, allowing an area of 10 x 10 meters to be tracked when four lighthouses are used and providing sub-millimeter accuracy), better scalability, and a higher field-of-view. (Valve Corporation [5]). An early version of this system was also described by Ben Jackson[16] at the Steam Dev Days (15:34-18:00): Instead of using a pair of rotors, the new version of the base stations uses only one rotor with the beams being slightly angled to resemble a V-Shape, which still allows the base stations to gather information for two axes.

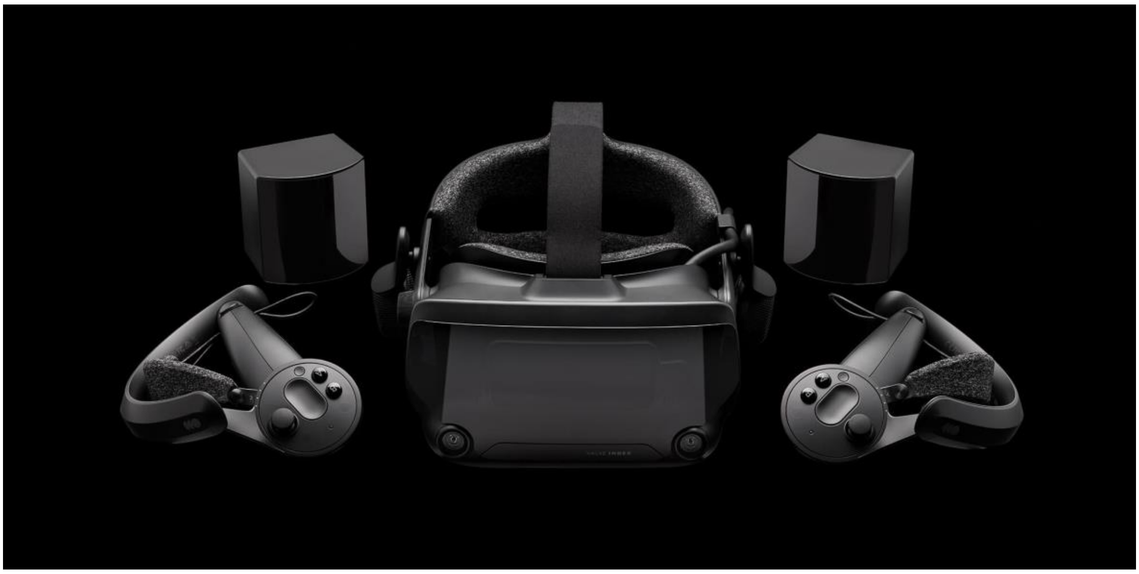

FIGURE 4: THE VALVE INDEX WITH ITS CONTROLLERS AND BASE STATIONS

The most popular VR headset according to Steam's hardware survey and the most recent one of the HMDs mentioned in this paper is the Oculus Quest 2, which released in October of 2020. In contrast to the Oculus Rift, HTC Vive and Valve Index, the Quest 2 is an all-in-one VR headset, which means that it does not require tethering to an external computer and can be used completely wirelessly. Additionally, it is also the cheapest one mentioned, with one version being available at around 300$. The display technology used is a single fast switching LCD screen with a resolution of 1832 x 1920 pixels per eye, offering a refresh rate of 72 Hz by default (Facebook Technologies, LLC.

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[16] Presentation of Ben Jackson on Valve's Steamworks Development Youtube-Channel, published online on 29.11.2016 - https://www.youtube.com/watch?v=BhzUn0gmkEU

[4]), though, since the release, software updates have increased the refresh rate to 90 Hz (Facebook Technologies, LLC. [1]) and recently 120 Hz (Facebook Technologies, LLC. [3]). While hand tracking can be used to recognize simple gestures like pointing and pinching, a new version of the Oculus Touch controllers is also supported, still allowing for the same gesture recognition that was used in the original Oculus Touch controllers (Facebook Technologies, LLC. [2]).

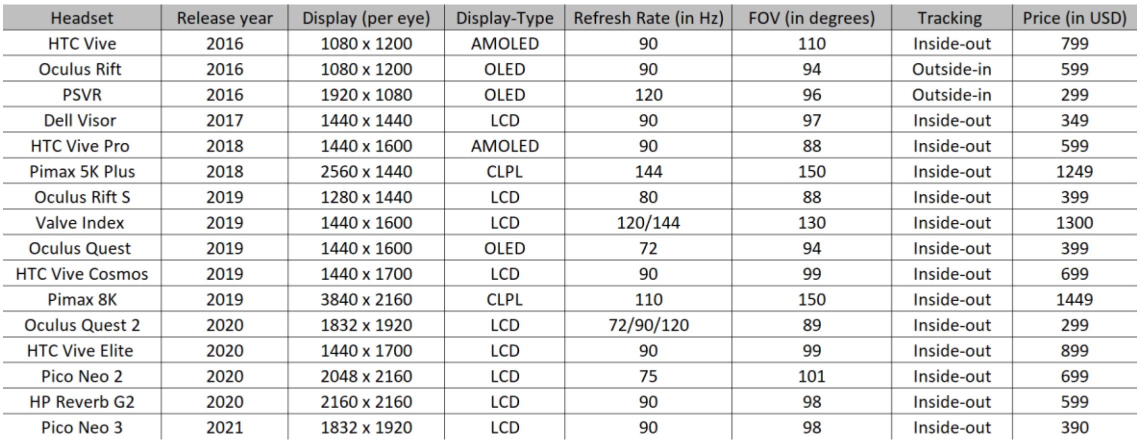
Since the Quest 2 is an all-in-one VR headset, no external tracking hardware is required. Tracking is handled through four cameras on the device, meaning that it uses optical inside-out tracking. According to one of Facebook's blog posts on the tracking system, computer vision algorithms and SLAM (visual-inertial simultaneous localization and mapping) are used in combination with AI to analyse the information provided by the device's sensors and calculate the headsets position and orientation. (Hesch et al., 2019). The Oculus Touch controller's positional and rotational values are being tracked through optical markers and the tracking system has an update rate of 1 kHz (Hesch et al., 2019), with Oculus recommending a tracked area of roughly 2.7 x 2.7 meters (Facebook Technologies, LLC. [4]). Holzwarth et al. (2021) found that the Quest 2's tracking system has a higher accuracy and precision than the Valve Index's, which leads them to say that the Oculus Quest 2's tracking system is "highly interesting for applications in research and industry, due to substantially lower acquisition costs, higher mobility, and faster setup" (pp. 7-8).

FIGURE 5: THE OCULUS QUEST 2, THE NEWEST VR HEADSET MENTIONED

4.3 OTHER EQUIPMENT

Most of the current virtual reality devices can be used in conjunction with external hardware that aims to improve the user's experience in various ways. This hardware can range from additional tracking devices to omnidirectional treadmills and even clothing items that can stimulate various senses, for example through haptic feedback.

The most well-known example for additional tracking devices are probably the Vive Trackers, which are designed to work with the SteamVR tracking technology of VR headsets like the HTC Vive and Valve Index. These additional trackers are relatively small and can be placed on a variety of objects, providing an easy way to track custom objects in the virtual world. For example, they can be mounted to a tennis racket and, once properly configured, can be used to resemble this physical object in the virtual world. Furthermore, they can also be used for a basic version of full-body tracking by attaching multiple sensors to the user's body (e.g., on their legs and hip). Navigation devices for virtual reality, especially omnidirectional treadmills, have recently become more popular and consumer friendly as well. One such device, the Omni One, is currently being prototyped by a company called Virtuix[17]. The Omni One, as well as many of the other omnidirectional treadmills and navigation devices, provides the user with an increased level of freedom to their movement (mainly for walking, running, crouching, and jumping; laying down is not possible in most omnidirectional treadmills), unrestricted by how much actual physical space the user has available to move around. Haptic feedback also plays an ever-increasing role in the simulation of virtual worlds, with devices such as the Teslasuit (developed by a company with the same name[18]) being a prime example for this. The Teslasuit can provide haptic feedback to the user across their whole body using electric impulses to stimulate muscles and additionally offers motion capture capabilities as well as biometric data, which can be useful for various research projects.



Headset	Release year	Display (per eye)	Display-Type	Refresh Rate (in Hz)	FOV (in degrees)	Tracking	Price (in USD)
HTC Vive	2016	1080 x 1200	AMOLED	90	110	Inside-out	799
Oculus Rift	2016	1080 x 1200	OLED	90	94	Outside-in	599
PSVR	2016	1920 x 1080	OLED	120	96	Outside-in	299
Dell Visor	2017	1440 x 1440	LCD	90	97	Inside-out	349
HTC Vive Pro	2018	1440 x 1600	AMOLED	90	88	Inside-out	599
Pimax 5K Plus	2018	2560 x 1440	CLPL	144	150	Inside-out	1249
Oculus Rift S	2019	1280 x 1440	LCD	80	88	Inside-out	399
Valve Index	2019	1440 x 1600	LCD	120/144	130	Inside-out	1300
Oculus Quest	2019	1440 x 1600	OLED	72	94	Inside-out	399
HTC Vive Cosmos	2019	1440 x 1700	LCD	90	99	Inside-out	699
Pimax 8K	2019	3840 x 2160	CLPL	110	150	Inside-out	1449
Oculus Quest 2	2020	1832 x 1920	LCD	72/90/120	89	Inside-out	299
HTC Vive Elite	2020	1440 x 1700	LCD	90	99	Inside-out	899
Pico Neo 2	2020	2048 x 2160	LCD	75	101	Inside-out	699
HP Reverb G2	2020	2160 x 2160	LCD	90	98	Inside-out	599
Pico Neo 3	2021	1832 x 1920	LCD	90	98	Inside-out	390

FIGURE 6: A COMPARISON OF A FEW OF THE CURRENT VR HEADSETS, SORTED BY RELEASE YEAR. THE SPECIFICATIONS FOR THE HEADSETS NOT SPECIFICALLY MENTIONED IN THIS SEMINAR PAPER HAVE BEEN TAKEN FROM A WEBSITE BY RORY BROWN, WHICH ALLOWS COMPARISON BETWEEN MANY DIFFERENT VR-HMDS - HTTPS://VR-COMPARE.COM/

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[17] Virtuix Inc. - https://www.virtuix.com/

[18] Teslasuit - https://teslasuit.io

5 OUTLOOK ON FUTURE DEVELOPMENT

In 1993, Gigante listed a handful of requirements for VR, based on their similarity to simulators at the time, a key aspect being that “like VR, simulators are only effective if, from the participants’ view, the experience is an accurate one” (p. 5). Many of the established requirements are still of importance today, such as rapid update rates, short lag times, and motion feedback, as well secondary visual clues through shadows and textures (pp. 5-6). According to Oculus’ documentation on working with their devices, display update rates below 60 Hz negatively affect the user experience (Facebook Technologies, LLC. [5]) and similarly Valve’s Nat Brown[19] gave 90 Hz as a recommendation at one of his talks at the Steam Dev Days (12:45-13:20). Seeing how many of the current devices support update rates of at least 90 Hz, which can be observed in Figure 6, it is safe to say that this can be viewed as a current standard in the industry, and it is unlikely that the display refresh-rate of future devices will fall below this value. Two other aspects are field-of-view and display resolution. As can be seen in Figure 6, the FOV of most current headsets rarely lies beneath 90 degrees. The same goes for display resolution. While the first-generation VR headsets like the Oculus Rift and HTC Vive offer a horizontal resolution of only 1080 pixels per eye, newer headsets frequently offer twice that resolution. On one hand, this can be attributed to the possibility of increasingly sharper displays due to processing hardware that becomes ever more powerful, as well as, on the other hand being a straightforward solution to the issue of having too few pixels per inch (e.g., the already mentioned screen-door-effect).

While many people nowadays have computer hardware that can handle virtual reality fairly well (the term “VR-Ready” has become a marketing term of sorts for computer hardware), the hardware requirements to allow for high-fidelity virtual reality experiences are still very high. According to the already mentioned hardware survey by Steam, the GTX 1060 graphics card by NVIDIA is currently the most owned GPU among steam users, with almost one-tenth using it. While this GPU fulfils the recommended minimum hardware requirements for most VR headsets on the market today, it does certainly not deliver enough performance for higher-resolution experiences with an acceptable refresh-rate.

Similarly, Matthews et al. (2020) also mention that currently available computer hardware and rendering requirements are “leading to a bottleneck in VR performance” (p. 398). Performance requirements are so high for virtual reality because, in the worst case, a scene must be rendered twice (once for each eye) to display virtual reality (p. 398). In their paper, Matthews et al. (2020) write about a solution to this problem, namely using eye-tracking to allow for foveated rendering (p. 398). Foveated rendering takes advantage of the limitations of the human visual system, allowing for rendering power to be focused on the parts of the screen that are in the central part of the user’s view (p. 398). Of course, foveated rendering is mainly done in software, but dedicated hardware is required to allow for eye-tracking. A few recent VR-HMDs are already capable of tracking the user’s eyes, though this technology is far from common in consumer VR headsets. In the future, eye-tracking hardware could become a standard part of virtual reality devices and might even be a necessity to keep up with the high computing demand of many new VR applications.

The issue around hardware requirements for virtual reality can also be solved by completely forgoing the need for dedicated hardware entirely and using the human

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[19] Presentation of Nat Brown on Valve’s Steamworks Development Youtube-Channel, published online on 04.11.2016 - https://www.youtube.com/watch?v=-a4lOkNRGxc

brain to generate virtual environments instead. In an interview[20], Gabe Newell, the founder of Valve, recently talked about Brain-Computer-Interfaces (BCIs) and how Valve is already researching this technology. He's of the opinion that BCIs will probably outperform conventional display methods by a long shot. Many movies and videogames, such as *Ready Player One*, *The Matrix* and *Cyberpunk 2077*, embrace this idea as well. In many of these fictional settings, a dystopian future is depicted, in which BCIs and the usage of BCIs to create a hyper-realistic virtual world is often shown in a negative light. As Gabe Newell also mentions in the interview, there are plenty of dangers and risk that come with this technology, but equally as many benefits. Of course, the technology for using BCIs to display vivid virtual reality environments is still only science fiction at this point, though one day it might entirely replace physical means of displaying VR.

Another hardware development that is currently not available, at least for consumer virtual reality devices, is advanced and realistic haptic feedback through the peripherals used in VR. Somewhat realistic haptic feedback for virtual reality is already possible through the use of different types of clothing, like vests and suits (e.g., the previously mentioned Teslasuit), but it is far from being common consumer VR hardware. Of course, while some people see this kind of hardware development as the future of virtual reality, which is definitely a valid point, many people are probably not willing to wear special-purpose clothing whenever they want to immerse themselves into a virtual world. An intermediate alternative to this could be realistic haptic feedback through already commonly used hardware like the VR headset itself or through the controllers that are used in conjunction with the headsets. A good example for this are the DualSense controllers that are used with Sony's[21] PlayStation 5. They can offer advanced haptic feedback based on what is happening in the game that is being played and the trigger-buttons on the back of the controller can give the user force feedback that is able to simulate different actions in a game, for example pulling the trigger of a gun or drawing the string of a bow back (Nishino, H., 2020), which can obviously increase immersion. Even though this technology has not been used actively in any consumer VR controllers so far, seeing how Sony has already developed a VR-HMD for the Playstation 4, it is not farfetched to assume that this kind of hardware could be featured in future controllers used in virtual reality.

As for virtual reality hardware that will be available in the foreseeable future, the HTC Vive Pro 2 and HP Reverb G2 Omnicept Edition are two VR headsets that have been announced. The Vive Pro 2 is the new version of the HTC Vive Pro, which released in 2018. It not only offers a much higher display resolution at 2448 x 2448 pixels per eye, but also has an increased FOV of 120 degrees, with the maximum refresh rate of the integrated LCD displays being 120 Hz and the headset being able to be used with a similar pair of controllers as the first version (HTC Corporation [2]). Tracking of the headset and its controllers is inside-out, as the tracking technology used is the same as in the Valve Index.

On the other hand, the Reverb G2 Omnicept Edition by HP[22] is one of the few VR-HMDs to incorporate foveated rendering through use of eye-tracking currently. Apart from the eye-tracking capability, the headset also offers other features such as a heart

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[20] 1 News interview with Gabe Newell, Founder of Valve - Article written by Luke Appleby (January, 2021) - https://www.tvnz.co.nz/one-news/new-zealand/gabe-newell-says-brain-computer-interface-tech-allow-video-games-far-beyond-human-meat-peripherals-can-comprehend

[21] Sony Group Corporation - https://www.sony.com

[22] HP Development Company - https://www.hp.com

rate sensor, face camera and motion tracking of the user’s arms (HP Development Company [1]). The headset itself uses two LCD displays with a resolution of 2160 x 2160 pixels each, refreshing with a rate of 90 Hz and providing the user with a FOV of roughly 114 degrees (HP Development Company [1]). Tracking of positional and orientational values for the headset and the controllers is done similarly to the Oculus Quest 2, using inside-out optical tracking (more specifically Windows Mixed Reality inside-out tracking) through four different cameras, two on the front of the headset’s body and two side-facing, in combination with inertial tracking through gyroscopes, accelerometers and magnetometers (HP Development Company [1]).

6 DISCUSSION

It is highly interesting to see the initial beginnings of virtual reality and its hardware and where it has come from. Since its early versions, inventions made in the field of virtual reality hardware have had an immense impact on a wide variety of different fields and extensive research has been done with it. Of course, this will hopefully continue in the future.

All in all, the developments in the field of virtual reality and its hardware in only the last decade are really remarkable. Software and especially hardware developments happen so fast that the information in this seminar paper will probably be somewhat outdated in just a year or two. Many of the different aspects of VR hardware mentioned in this paper will probably change or maybe even disappear entirely in the future. Possibly, some completely new aspects will be of importance instead. Hardware that helps take advantage of the limitations of human senses, like the eye-trackers, could easily become a staple component of future virtual reality headsets. Optical tracking is currently the by far most used tracking method, but that could also easily change if a superior tracking method (maybe even an entirely new type of tracking) becomes available in the future. While it seems a lot like science fiction right now, maybe in 50 years Brain-Computer-Interfaces will be so advanced that the need for a virtual reality headset, or any external hardware for that matter, will become completely obsolete and the entire processing of the virtual world is done via the human brain. Regardless of what type of hardware may or may not be used for virtual reality, if the current hype around this technology and the technological innovations continue like they do right now, virtual reality has a bright future ahead of itself.

7 LIST OF FIGURES

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Some of the sources are websites of manufactures and companies behind the mentioned hardware (e.g., blog entries, specification sites of different HMDs, etc.) that do not have specific authors or dates available, to reference these in the text in a readable manner an index in the shape of '[#]' has been added behind their respective company's name.

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