Overview of Controllers of User Interface for Virtual Reality

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Abstract Virtual reality has been with us for several decades already, but we are still trying to find the right ways to control it. There are a lot of controllers with various purposes and means of input, each with its advantages and disadvantages, but also with specific ways to be handled. Our hands were the primary means of input for human-computer interaction for a long time. However, now we can use movements of our eyes, our feet or even our whole body to control the virtual environment, interact with it, or move from one place to another. We can achieve this with various controllers and wearable interfaces, like eye tracking, haptic suits or treadmills. There are numerous devices that we can choose from for every category, but sometimes it can be hard to pick the one that suits our intentions best. This article summarises all types of user interface controllers for virtual reality, with their main pros and cons and their comparison.

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1 Declarations

1.1 Funding

This research has been supported by GACR grant No. GA18-18080S.

1.2 Conflicts of interest

The author(s) declare(s) that they have no competing interests.

1.3 Availability of data and material

Not applicable.

1.4 Code availability

Not applicable.

1.5 Authors' contributions

TN carried out the research of the controllers. MJ provided reviews and notes about the structure and the content of the article. All authors read and approved the final manuscript.

2 Introduction

Virtual reality is one of the fastest-growing fields in today's technology. The visual quality, the field of view, the time-warping, it all gets better and better every day. However, there is also one other important aspect of virtual reality that is not discussed that often, yet it should be – user interface.

After several decades of being dependent only on a mouse and a keyboard – devices which prevailed as controllers for personal computers – we can finally use other input methods. To control the virtual environment, we can even use different parts of our body other than hands (for example, eyesight for eye-tracking) or let our own feet carry us around the virtual world. Nevertheless, it may be hard for us to start thinking about movement and visualization in 3D after years of being accustomed to the 2D computer planes (Bernatchez & Jean-Marc, 2007).

Any interaction mechanism from the real world can be simulated in VR (LaValle, 2019), says the Universal Simulation Principle by LaValle. But how can we simulate such interactions as typing on a keyboard or handling a scalpel? What is the technology that will be the most natural for the user? How can we achieve the feeling that the user is part of the virtual world and can interact with it as with the real world?

Currently, there is a myriad of controllers for VR, each with its benefits and limitations. Our goal is to compare and revise them and find the most promising approach that will prevail in the following years. Even though some discussed devices were not successful in sales or were only in a prototype stage, some knowledge can be extracted from them. It can still show us what the users liked or what did not work.

We expect many new devices to appear in the marketplace in the coming years. However, as you will see in the following pages, the fundamentals and the concept remain the same even in the face of the ever-changing and ever-evolving field of information technology. Knowledge of past and present technology provides concrete examples to clarify the fundamental VR concepts and foreshadow what will come in the following years.

But how to say what devices will survive the constantly revolving wheel of time? The one that is easiest to work with or the one that is the most realistic? These questions are difficult to answer and not enough for making a final descision because of how human physiology and perception operate and interact with engineered systems. By contrast, pure engineering questions, such as "What is the battery life of the controller?" or "What is the distance the sensors signal can reach?" are much more approachable.

Also, some devices are easier to learn than others. For example, getting the hang of working with a computer mouse does not take long, but typing quickly on a keyboard with all ten fingers takes years to master. What makes one device easier to learn than another? It is often very hard to say; because there are always many variables that have to be taken into account. A good example is the backwards brain bicycle, which was introduced by Destin Sandlin to show how small changes in interaction can have significant consequences on user experience. Destin reversed the steering operation of the bike so that turning the handlebars left turns the front wheel to the right (Sandlin, 2021). Even though Destin mastered riding the regular bike when he was a young boy, now it took him eight months to ride the backwards bike.

However, it is impossible to find a silver bullet – a controller that would cover all possible applications. Where surgeons need controllers with submillimeter precision to train for heart surgeries, but gamers need an easy way to shoot zombies or fly a plane. Such diverse use cases mean that we need diverse controllers that support a wide range of actions.

The controllers for VR can be divided into groups by two main criteria – by the means of input, such as hand-based or feet-based, and the technology used for the measurements, like optical or acoustic tracking. We created the taxonomy in figure 1, which is first divided by the means of input, then by the technology. One of the goals of this research is to further expand the taxonomy by the information about its usability and complexity in their corresponding section.

Comparing all the existing controllers and approaches could help us or any of the readers create their own controller or user interface that can move or even break the limits of interaction in virtual reality.

Most tracking devices can also create more realistic avatars (virtual representations of the user) because the avatar is then more life-like. It looks, moves and acts like the user, or at least a fine representation of real human beings, which can help multi-player environments or VR calls.

The following article summarises different kinds of controllers for extended reality – virtual reality (VR) and augmented reality (AR) – their types according to the primary means of input and their pros and cons.

Several articles provide (e. g. Bachmann et al., 2018, Sudha et al., 2017, Perret and Poorten, 2018, Y. Li et al. (2019), Boletsis and Cedergren, 2019) some summary of some of the devices, but not to the extent of this article, especially regarding the depth of the research and the number of types and devices.

Since this is a summary of practical devices, where most of them are used either in industry (for designers, work simulators), research (human-computer interface, medicine) or by individuals (amateur developers, gamers or reviewers), the insight of everyday users is crucial. When controllers of a user interface are discussed, the opinion and experience of everyday users are important because the quality of the user interface controller can only be measured by the satisfaction of the users with it.

This is why references of this summary include not only research papers and official technical specifications but also user reviews and comments from other than just academic sources.

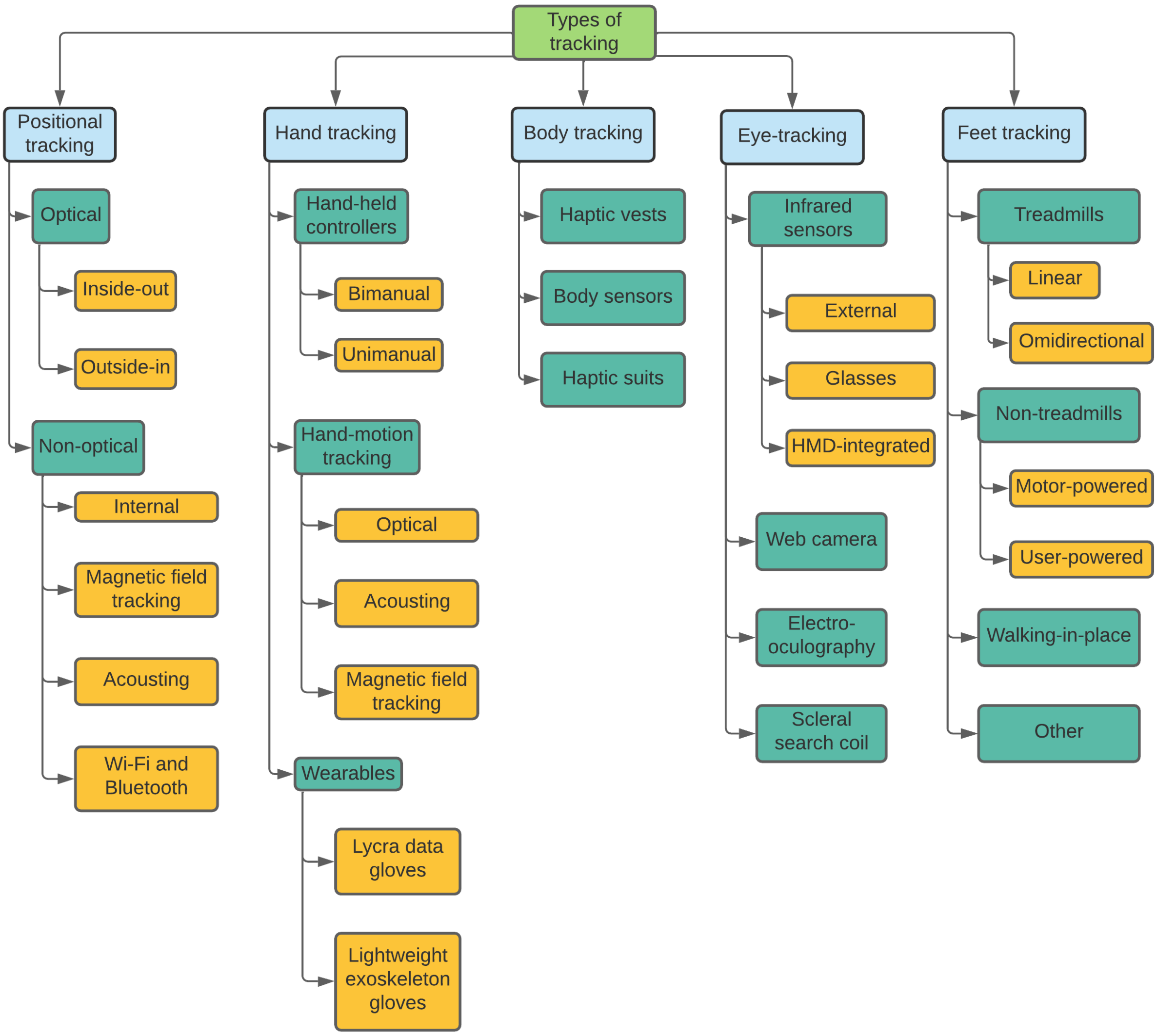

Figure 1 Taxonomy of controllers

The rest of the paper is structured as follows. In Section 3, we discuss tracking, which is used to determine the position of the tracked object (user or controller) in the tracked space. In Section 4, we summarize controllers which are based on user's hand and finger movement. Section 5 describes various ways how to track and provide feedback to the user's body. In Section 6, technologies and corresponding devices to track user's eyes are listed. Section 7 covers the topic of transferring motion of the user's legs and feet to the virtual environment.

3 Positional Tracking

The times where we sit at the computer are long gone. With virtual reality, we need to move from one place to another, and it does not matter if we are walking through Pompeii right before its doom or searching for some artefacts in a galaxy far far away. One of the most popular ways how to achieve this is motion tracking.

Motion tracking (sometimes called digitization of motion) is becoming more popular nowadays because it enables the user to act naturally – walk, move their feet, hands or even fingers, and all that motion can be transferred to the virtual world.

Motion tracking is also essential for the movie industry. The movement of the actor's body or even face muscles is captured and then transferred into the movement of the computer-generated character – it can be an orc or even some magical beast like a fire-breathing dragon. This can also help create virtual avatars in virtual reality, which can help to create really immersive experience.

Positional tracking is a type of motion tracking that provides information about the user's position in the tracked space (e.g., a room). The main advantage is that no additional controller is needed, and the user can move freely with 3 DOF (with yaw, pitch and roll) or even 6 DOF (movement in x, y, z axes). The main disadvantage is that the tracking range limits the user (the maximum distance between the tracking sensor and the tracked object), the precision of the tracking as well as the size of the tracked space (e.g., room)[1].

Positional tracking consists of two major types – **optical tracking** and **non-optical tracking**. Optical tracking uses cameras to track the users according to special markers. Non-optical tracking itself splits up into a myriad of categories, where the majority is based on inertial measurement units – IMU (magnetometers, gyroscopes, and accelerometers). Still, the more advanced options can use magnetic field tracking or acoustic tracking. (Antytip, 2020) Optical tracking, in general, is the most common positional tracking for virtual reality. However, most modern positional tracking systems combine optical and

[1] A psychological solution to the limitation by the size of the room is worth mentioning. If the virtual world is slightly curved, the user will slightly turn in the real world without knowing it, even though it feels as if they walked straight. This is called redirected walking. However, the room has to be large enough for the user not to feel any inconsistency between the straightforward movement in the virtual world and the bent movement in the real world. (Bruder et al., 2015) Another approach is saccadic redirection (saccade is a quick, simultaneous movement of both eyes), where the redirection is made during eye movements, making it undetectable for the user. This approach does not require as much space as basic redirected walking, but eye-tracking has to be used for detection of the saccades. (Sun et al., 2018)

non-optical tracking systems to achieve higher accuracy. These systems are called hybrid tracking systems. (ART, 2020a)

Motion tracking does not only refer to positional tracking – it can also be used for tracking users' hands and fingers. For devices that use hand and finger tracking, see Section 4. However, only sometimes tracking of the user's hands is not enough and capturing the movement of the whole body is required – for information about (full) body tracking, see Section 5. For locomotion tracking systems, based on the movement of users' feet, see Section 7.

3.1 Optical Tracking

Optical tracking of the user's movements is the most used type of positional tracking, thanks to its simplicity and usage of already established and well-developed technologies.

Optical tracking uses a kind of imaging device (e.g., a camera) to track the user. There is a source (generally more than one, usually placed on the walls of the tracked room) that sends an optical signal (e.g., an infrared light) captured by the imaging device, and the user's position is calculated. If the signal is generated by the imaging device and then reflected to the source by special markers (either worn by the user or placed in the environment, e.g., walls), it is called **passive optical tracking**. If the signal is generated by the markers (usually by LEDs) and sent straight to the imaging device without the need for any reflection, it is called **active optical tracking**. With active optical tracking, the user has to wear or be connected to some power source to generate the signal, making it less convenient for him. However, it is more accurate than passive optical tracking (Tjaden et al., 2015).

When the signal reaches the imaging device, it is used to calculate the distance from the source, and the marker is assigned to a 3D model that recreates the tracked object.

A completely different approach is used by **markerless tracking**, which uses model-based approaches or image processing by comparing the known 3D model of the scene. It scans the environment by either an optical or a non-optical approach, extracts feature points (edges, corners etc.) and compares the points to a preloaded model of the environment. When the two models match, the position is determined (Marxent, 2020) (XinReality, 2020c) (XinReality, 2020a) (XinReality, 2020b). Unfortunately, there has to be enough feature points to work with – it does not work with blank walls or other surfaces without texture detail.

3.1.1 Outside-in Tracking

Outside-in tracking is the most common type of optical tracking nowadays, even though inside-out tracking (Section 3.1.2) has become increasingly popular in the last few years. Outside-in tracking means that the optical sensor is placed outside the tracked device and uses an approach with or without markers to determine the user's position. Outside-in tracking with markers consists of one or more stationary cameras placed on the boundaries of the tracked space, and the markers are placed on the tracked object. Outside-in tracking without markers uses feature points (e.g., edges, wrinkles) on the user's body or the tracked device.

Pioneer of the customer everyday motion tracking was supposed to be Microsoft's first generation of **Xbox Kinect** (2010) (Cong & Winters, 2020). It consists of an RGB video camera, depth sensor and multi-array microphone (see figure 2). This first generation was based on the structured light principle, where an infrared pattern is projected onto the user. The camera detects deformations of the pattern and computes the distance and gestures of the user accordingly. Forty-eight points on the user's body are detected and tracked, with a refresh of the detection every 30 seconds. This enabled the user to control the virtual environment only with body movements. Unfortunately, Kinect was not a commercial success, and even the second generation successor's sales turned out to be disappointing.

Figure 2 Xbox Kinect (jhersson, 2020)

The second generation was based on the Time of flight (TOF) principle (tracking the time of the signal getting to a tracked object and back to the source). Microsoft ended Kinect's support in 2017 (Sarbolandi et al., 2015). In 2020, Microsoft released **Azure Kinect**, a tracking device in a new line of sensors, this time not for gaming but industry and business. It is also based on TOF and uses a

12-megapixel RGB camera supplemented by one megapixel-depth camera for body tracking and a 7-microphone array for speech recognition (Microsoft, 2020d).

One of the most used motion tracking systems that are based on optical sensors is ART – Advanced Realtime Tracking (ART, 2020b). ART provides several outside-in tracking sensors (like **TRACKPACK**, released in 2015 for larger spaces, or **SMARTTRACK**, released in 2019, for desktop/wall tracking) that use both active and passive markers. The quality of the tracking depends on the number of tracking cameras. The precision and the number of DOF depends on both the number of cameras and the number of markers. ART also provides a clip-on for head-mounted displays (HMDs).

OptiTrack's **Prime$^{\text{x}}$ 41** (2012) (OptiTrack, 2020a) promises 30.5 meters tracking range with passive markers and 46 meters with active markers. It can be combined with any OptiTrack's Prime camera to create the optimal configuration for any use case. The camera also changes its status-indicating colour (green for a valid state, red for an error state) according to its state (connected, recording, etc.), see figure 3. The camera can be used outside in bright sunlight; however, the range reduces by half. OptiTrack also has a desktop-mounted device, **V120:Trio** (2011) (OptiTrack, 2020b), a plug-and-play bar with three cameras supporting 6 DOF.

Figure 3 OptiTrack's Prime$^{\text{x}}$ camera (OptiTrack, 2020a)

In 2016, WorldViz released **Precision Position Tracking (PPT)** (WorldViz, 2020a), a tracking system with a warehouse-scale (the tracking should be precise within an area greater than 50 x 50 meters). It supports interface integration not only for WorldViz's Vizard (WorldViz, 2020b), but also for Epic Game's Unreal (Epic Games, 2020) and Unity Technologies' Unity (Unity, 2020), and it boasts multi-user collaboration as well as having its own hand controller. The optical tracking can be improved by an inertial tracking system (inside the controller and/or as an HMD clip-on).

Vicon (Vicon, 2020b) is one of the oldest motion-capture companies in the world. It was founded in 1984, and since then, they have developed several record-breaking tracking solutions (in 2019, they tracked 35 people simultaneously) with their **Vantage** (2015) (Vicon, 2020a) tracking cameras. It is one of the few companies which provides a full-body marker suit to track the users. However, marker stickers are also available. With specific settings, the Vantage camera can provide sampling frequency up to 2000 Hz.

VR Tracker (2016) (VR Tracker, 2020) by the company of the same name provides a tracking system that can also work wirelessly via Wi-Fi. The battery can last up to 3 hours. The tracker also provides what the company calls 9 DOF (regular 6 DOF and additional information about velocity in x, y and z-axis directions).

Constellation (2015) (XinReality, 2020d) by Oculus VR is a tracking solution for Oculus Rift devices, but it is said to have poor quality (Durbin, 2017).

PlayStation VR (2016) (PlayStation, 2020a) by PlayStation has two cameras-bar to track blue strips of light on the headset and orbs of light on PSVR controllers (see figure 4). In contrast to other optical tracking, PlayStation VR tracking uses a visible (RGB) light spectrum for tracking.

Figure 4 PlayStation VR with active tracking markers (PlayStation, 2020a)

Mo-sys, a company that specializes in high-end cameras, created **StarTracker** (2017) (Mo-sys, 2020), a tracking camera that is made for studio tracking.

Motion Analysis company provides optical tracking for motion capture high-resolution cameras (like **Raptor 12HS** (2015) (Motion Analysis, 2020)) that can be used for VR positional tracking. Qualisys provides several tracking cameras (like **Miqus Hybrid** (2019) (Qualisys, 2020)) that support tracking both with and without markers, and they even have a camera that works underwater. Intersense, which is commonly known for its acoustic tracking, released its newest optical tracking camera **IS-1500** in 2016 (Intersense, 2020).

3.1.2 Inside-out Tracking

With inside-out tracking, the camera is placed on (or inside) the tracked device (for example, HMD) and the markers (either artificial markers for tracking with markers or feature points for tracking without markers) are placed in stationary locations (e.g., walls). Inside-out tracking often works on the passive-markers principle, so it does not need any other devices (sources of the signal that are common for outside-in tracking) to operate.

That being said, the most common inside-out tracking, made by Valve, uses active markers. Valve's tracking, dubbed **Lighthouse** (2015) (Valve, 2020c), is developed mainly for SteamVR (Valve, 2020b) and HTC Vive, but it can be used for other HMDs also. This tracking is often wrongly categorized as outside-in tracking because it uses two "base stations" – boxes emitting an infrared signal (see figure 5). The signal is not sent back to the base station; it is captured by the photosensors on the HMD (and optionally HTC Vive controllers). The device then the location of the tracked object according to the difference in the acquired infrared signal waves. Thus, the tracking is made by the device itself, making the tracking inside-out. This system does not use any cameras for tracking.

In 2019, Valve presented **HTC Vive Cosmos** (Valve, 2020d), which does not use Lighthouse tracking system, but it has true inside-out tracking. It has six built-in sensors – four in the front (to scan ahead, above, and below the headset) and one for each side. Lighthouse backward compatibility is promised for the year 2020; however, in October 2021, it still was not working. (Machkovech, 2020) Vive's business standalone headset, **HTC Vive Focus** (Valve, 2020a) with inside-out tracking, was released in 2019.

Figure 5 HTC Lighthouse base station (VIVE, 2019)

Google's **WorldSense** (a feature integrated into Daydream Standalone headsets (Google, 2020a) (Googles's VR operating system), first of which was Lenovo's Mirage Solo (2018) (Lenovo, 2020b)), is markerless inside-out tracking that works both indoors and outdoors and in both dim and bright lighting.

Facebook created **Insight** (tracking system integrated into Oculus Quest (2019) (Oculus, 2020a) and Oculus Rift S (2019) (Oculus, 2020b)). Built-in cameras create a 3D model of the room (see figure 6), IMU system tracks head and hand movements, and infrared LEDs in the controllers make the tracking of the controllers more precise, thus promising submillimeter precision. (UploadVR, 2019)

Figure 6 Visualization of Oculus Insight inside-out tracking (Graham, 2018)

IndoTraq's **HSVT – High-Speed Vision Tracking** (2018) (IndoTraq, 2020) combines optical inside-out tracking with RF tags to create precise tracking that works even with the occlusion of the cameras.

Microsoft's **Hololens 2** (2019) (Microsoft, 2020a) also provides inside-out tracking, using Azure Kinect's 3.1.1 depth camera (Acer, 2020). Prior to Azure Kinect, Microsoft focused on Windows Mixed Reality tracking, which was later integrated into several HMDs, like Acer Windows Mixed Reality Headset (vGIS, 2020).

Antilatency provides **Alt** tracker (2019) (Antilatency, 2020) that the company claims is the smallest tracker in the world (the module is only 16x16x20mm in size and weighs only 12 grams). The tracker combines IMU data with data from active marker optical sensors and does most of the processing, so the VR/AR device gets only the result data. Because every tracker works independently, there is no limitation when the number of users is concerned.

Occipital's inside-out tracking called **Structure core** (2016) (Occipital, 2020) is integrable in other AR and VR devices along with their depth camera. Stereolabs' **ZED 2** (2020) (Stereolabs, 2020) enables simultaneous localization and mapping of the environment, floor plane detection and skeleton tracking, as well as compensation of error caused by the rising temperature of the camera during operation. In 2019, Intel released its **RealSense T265** (Intel RealSense, 2020) tracking camera with two fisheye lenses but no depth camera.

3.2 Non-optical Tracking

Non-optical tracking uses internal tracking directly integrated into the hardware (like HMDs) or support devices attached to the body that measure and track the movements. The subcategories are internal tracking, magnetic field tracking, acoustic tracking or Wi-Fi/Bluetooth tracking. Apart from optical tracking systems, non-optical tracking systems do not rely on cameras, markers and feature points but use magnetic waves, sound waves or radio-frequency. That enables them to work even with occlusion (without direct line of sight), but they suffer from distortion by waves created by other devices.

The main three non-optical tracking categories differ by the tracking approach, where most devices use **internal tracking** IMUs, some use **magnetic field tracking** based on electromagnetic fields, **acoustic tracking** is based on sound waves and **Wi-Fi and Bluetooth tracking** utilizes common Wi-Fi and Bluetooth modules to determine the user's position.

3.2.1 Internal Tracking

Internal tracking devices are magnetometers, gyroscopes, and accelerometers (IMU). Magnetometers are used to measure the strength and direction of the magnetic field in the vicinity of the instrument. (Speight, 2019) Gyroscopes measure the rate of change in object orientation or angular velocity. Accelerometers measure acceleration and can be used to determine the object position if the starting point is known. (Shawn, 2019) This approach is used basically in all current HMDs with more or less the same system and precision, so they will not be discussed here.

3.2.2 Magnetic Field Tracking

Magnetic field tracking is a tracking solution based on the electromagnetic field. The device consists of a magnetic field generator (Source) and magnetic field processor (Sensor/Hub), all tuned to a specific frequency. The source is sending baseline magnetic fields tuned to specific AC (alternating current) or DC (direct current) frequencies (Rodgers, 2011). However, magnetic field tracking can suffer from measurement distortions due to ferromagnetic metals (ART, 2020a), and the tracking distance is very short compared to optical tracking. AC tracking works on the principle of the continuously changing magnetic field generated by AC magnetic trackers inducing currents in the receiver's coils (i.e., antennae). DC trackers transmit a short series of static magnetic fields to avoid the eddy current generation. Once the field reaches a steady state, the measurement is taken with the help of flux-gate magnetometers (Mazuryk & Gervautz, 1999). AC tracking systems are more accurate and faster than DC systems.

Polhemus G4 (2010) (Polhemus, 2019) is the main representative of magnetic field tracking. Multiple sources with multiple DC frequencies can be used. The Sensor/Hub receives those frequencies and interprets them, computing the specific position and orientation that can be acquired for each channel. The information is then sent back via RF link. (Rodgers, 2011) In February 2020, Polhemus released **Viper** (Polhemus, 2020), their new generation of tracking system.

Another commercially used magnetic field tracking system is Ascension's **trakSTAR** (2010) (Ascension, 2014). trakSTAR uses AC to track the targets and is mainly used for medical fields (tracking probes, scopes, needles, catheters, etc.).

Sixence's **STEM system** (2013) (Sixense, 2013) was supposed to be groundbreaking magnetic-field tracking technology; however, after years of development, the tracking system was abandoned.

3.2.3 Acoustic Tracking

Acoustic tracking is based on Doppler shift, where the signal frequency changes as a sender or receiver moves. (Mao et al., 2016) The sound waves propagate slowly, making the tracking highly accurate on short distances but ineffective on the longer range. Many devices have good speakers and microphones that can be used for tracking, and the time needed to process the data is low due to its low sampling rate. However, this technology is significantly less accurate in a noisy environment. Acoustic tracking is mostly used for tracking fingers in a close range of the device because it was proved imprecise on the longer range.

One of the only systems that have used acoustic positional tracking is the **Logitech 3D mouse and head tracker** (1991) (VR Depot, 2020). The system consists of two transmitters (for the head and mouse), two receivers (head and mouse) and a control box that processes the signals. The tracker software calculates the receiver's position based on triangulation from the relative times of the three ultrasonic signals.

In 2016, Lyrobotix was reported (Lang, 2016) to work on a tracking system **NOLO** that uses both acoustic and optical tracking. The system can be used for a variety of VR headsets because it comes in the form of a sphere connected to the headset. The provided emitter sends ultrasonic and laser signals through the room and the sphere, covered in receivers, processes the signal and computes the user's position. The device can be seen in figure 7).

Figure 7 NOLO acoustic tracking (Zhao, 2017)

Intersense, a company that was created as an extension of the Massachusetts Institute of Technology (MIT), presented their first acoustic-based tracking system, **Constellation**, on SIGGRAPH in 1998 (XinReality, 2020d). Ten years after that, they released a widely-used acoustic tracking system **IS-900** (2008). This system also combines data from acoustic sensors and IMU and provides both cable and wireless solutions. Even though the company created a new device, IS-1500 (see 3.1.1), that uses optical tracking, IS-900 is still on sale. Company **5DT** (5DT, 2020b) used to have its own ultrasonic tracking, but no information about it is now available.

3.2.4 Wi-Fi and Bluetooth Tracking

Wi-Fi/Bluetooth wireless tracking uses Wi-Fi and Bluetooth transponders that are very common and easily affordable. However, this technology is prone to errors due to a variety of incoming signals, and the precision often varies from 1–10 meters with latency in hundreds of milliseconds (IndoTraq, 2018).

Researchers from University College London created **ArrayTrack** (2013) (Xiong & Jamieson, 2013) where they use Wi-Fi access points in an office building to track users with 23 cm accuracy just with the use of their phones. ArrayTrack computes the user's position from the data sent by the user's phone via the network.

IndoTrack (2017) (X. Li et al., 2017) is a system that uses Wi-Fi (one transmitter and two receivers) to track users indoors via their cellphone. The system uses the Doppler effect to track the user's location and velocity to calculate his exact position over time.

WiCapture (2018) (Kotaru & Katti, 2018) is a Wi-Fi tracking system made especially for VR. The Wi-Fi chip integrated into any headset transmits packets that are received by standard Wi-Fi access points. The access points mine the packets' metadata to recover the position. The system is occlusion resistant. The same approach is used by **SpotFi** (2015) (Kotaru et al., 2015).

Other systems that use Wi-Fi for user's localization are, for example, **SpinLoc** (2015) (Sen et al., 2012) or **ToneTrack** (2015) (Xiong et al., 2015).

3.3 Summary

The following table is a summary of the positional tracking systems. Only one (the best) tracking from every company is stated; however, it can be stated in two versions (of one product). Only the corner versions (e. g., minimal and maximal frequency) are then provided. In that case, the label of the version is in parenthesis in italic, after the name of the product.

Table 1: Summary of positional tracking systems

Device	**Freq.**	**Lat.**	**Acc.**	**Res.**	**FOV**	**# tar.**	**# sen.**	**Range**	**Tech.**	**Status**
Xbox Kinect	30	<80	18	640x480	84.1x53.8°	2	1	3.5	M	NFS
Azure Kinect	30	12.8	N/A	640x576	75×65°	N/A	1	N/A	M	CU
SMARTTRACK3 *(150Hz)*	150	<10	N/A	1280x1024	120x93°	4	1	3	AM+PM	CU
SMARTTRACK3 *(240Hz)*	240	<10	N/A	1280x660	120x70°	4	1	3	AM+PM	CU
TRACKPACK/E *(Resolution)*	60	<20	N/A	1.1 MPix	97x74°	20	8	4.5	AM+PM	CU
TRACKPACK/E *(Speed)*	120	<20	N/A	0.5 MPix	97x39°	20	8	4.5	AM+PM	CU
Prime^{x} 41 *(180Hz)*	180	<20	0.01	2048x2048	51x51°	25	N/A	46	AM+PM	CU
Prime^{x} 41 *(250Hz)*	250	<20	0.01	2048x1440	51x35°	25	N/A	46	AM+PM	CU
V120:Trio	120	8.3	N/A	640x480	47x43°	N/A	1	N/A	AM+PM	CU
Precision Position Tracking	240	4.2	<1	1280x1080	82x?°	10	N/A	N/A	N/A	CU
Vicon Vantage *(V16)*	120	8.3	N/A	16MPix	76.4x76.4°	35	N/A	N/A	AM+PM	CU
Vicon Vantage *(V5)*	420	4.7	N/A	5MPix	63.5x55.1°	35	N/A	N/A	AM+PM	CU
VR Tracker	50	N/A	<0.5	5MPix	90x90°	16	N/A	N/A	AM	CU
Constellation	60	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	CU
PlayStation VR	N/A	N/A	N/A	N/A	72x45°	3	1	4.6	AM	CU
StarTracker	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	CU
Raptor 12HS	300	N/A	N/A	4096x3072	64x50°	N/A	N/A	N/A	PM	CU
Miqus Hybrid	340	N/A	N/A	1920x1088	61x37°	N/A	N/A	N/A	PM+ML	CU
IS-1500	N/A	20	2	N/A	N/A	N/A	N/A	N/A	ML	CU
HTC Vive (Lighthouse)	250	15	0.3	N/A	160x115°	unlim.	4	7	ML	CU
HTC Vive Cosmos	N/A	N/A	N/A	N/A	N/A	4	2	N/A	N/A	CU
HTC Vive Focus	N/A	N/A	N/A	N/A	180x140°	2	2	N/A	N/A	CU
WorldSense	N/A	N/A	N/A	N/A	N/A	2	2	N/A	ML	CU
Oculus Insight	N/A	N/A	N/A	N/A	N/A	2	2	N/A	ML	CU
IndoTraq	150	6	<0.01	N/A	N/A	16	8	N/A	ML	CU
Hololens 2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	ML	CU
Alt	2000	2	<1	N/A	N/A	unlim.	unlim.	100x100	AM	CU
Structure core	60	N/A	N/A	1280x960	70x?°	N/A	N/A	<5	ML	CU
ZED 2 *(2.2K)*	15	N/A	N/A	4416x1242	110x70°	N/A	N/A	N/A	ML	CU
ZED 2 *(720p)*	60	N/A	N/A	2560x720	110x70°	N/A	N/A	N/A	ML	CU
RealSense T265	N/A	<6	N/A	848x800	163x?°	N/A	N/A	<5	ML	CU
Polhemus G4	120	<10	1.27	—	—	N/A	N/A	3	M	CU
Polhemus Viper 16	960	1	0.38	—	—	N/A	N/A	1.8	M	CU
trakSTAR	420	N/A	N/A	—	—	4	4	0,66	M	CU
Logitech tracking	50	30	N/A	—	—	N/A	N/A	1.5	A	CU

Table 1: Summary of positional tracking systems

Device	Freq.	Lat.	Acc.	Res.	FOV	# tar.	# sen.	Range	Tech.	Status
NOLO	60	<20	2	—	N/A	4	1	4	A	CU
IS-900	180	4	<3	—	N/A	N/A	N/A	N/A	A	CU
ArrayTrack	40	4	23	—	—	N/A	N/A	N/A	W	PR
IndoTrack	200	N/A	35	—	—	N/A	N/A	N/A	W	PR
WiCapture	167	N/A	0.25	—	—	N/A	N/A	N/A	W	PR
SpotFi	N/A	N/A	40	—	—	N/A	N/A	N/A	W	PR
ToneTrack	500	N/A	<60	—	—	N/A	N/A	N/A	W	PR

Freq. – reported data frequency in hertz

Lat. – latency of the system (lag) in milliseconds

Acc. – accuracy of the reported position in centimeters

Res. – resolution in pixels

FOV – field of view (horizontal x vertical)

 # tar. – the maximum number of tracked targets

 # sen. – the maximum number of sensors for one controller

Range – the maximum range of the tracker in meters

Tech. – technology – markers (AM – active markers, PM – passive markers, Ml – markerless, M – magnetic, A – acoustic, W – Wi-Fi)

Status – the status of the tracking (CU – commercially used, NFS – not for sale, PR – prototype)

N/A – information could not be found

— – information not relevant for this device

3.4 Discussion

The variety of different approaches for positional tracking shows that it is very important for further improvement of the immersivity of virtual reality. To allow the user to move naturally while in the virtual world is crucial. It provides simple and precise information about the user's position, often without the need for the user to wear some extra hardware, that is not built or attached to the head-mounted display.

Outside-in and inside-out optical tracking combined with internal IMU tracking seem like the most promising approaches because of their simplicity and range of tracking. Inside-out tracking will most probably prevail for small-scale applications like gaming at home because the environment provides enough points of interest (objects, edges) that can serve as natural markers. On the other hand, outside-in tracking will be used in large-scale applications, where multiple users are tracked because the same sensors can track all of them. The size of the tracked space can be easily scaled by just adding more sensors.

However, the space constraints are still a big drawback for positional tracking, and it is a drawback that will be very hard to solve. If you need for the user to cover great distances, it would be better to use one of the Locomotion approaches (see section 7), because the available space does not limit them.

The other problem with basic positional tracking, where only the head's tracking is taken into account, is that even though the avatar moves in the virtual world, there is no information about the rest of the body. So if the user bends, leans to the side or crouches, there is no way to distinguish these movements – the tracking only detects that the sensor's position changed.

This can be solved by tracking multiple points on the user's body. However, it then moves to the section of full-body tracking 5 than simple positional tracking.

Acoustic and magnetic field tracking suffers too much from interference from other sources, so even though this approach is interesting, it does not provide the usefulness of optical tracking.

Wi-Fi tracking can help track users in buildings or tunnels as an addition to GPS tracking, which does not work precisely indoors. However, its usage in virtual reality is limited.

4 Hand-Based controllers

Hand-based controllers have dominated the way we work with virtual environments for several decades, and it does not seem it will change anytime soon. Even though controllers that use our full body (Section 5) or our feet (Section 7) are getting more and more popular, they will probably only complete hand-based tracking to provide a fully immersive experience. However, hand-based tracking will still prevail because hands are our primary tool (Guiard, 2013).

The need for simple interaction with our hands is evident. However, not all approaches are enough for all applications. In one virtual world, we need just a controller in the form of a stick to have a feeling like we are holding a sword, and the precision of one centimeter does not make a difference when you slay a dragon. In a virtual world where you are a surgeon who performs heart transplantation, every millimeter can make the difference between life and death.

Precision is not the only vital point of hand-based interaction. The feedback from the device can not only provide a more immersive and realistic experience but can be crucial to the application outcome. For example, providing force feedback is important in developing medical devices that enable doctors to perform surgical procedures through an interface connected to an actual device. Without accurate and timely haptic feedback, it is difficult for doctors to perform many procedures (LaValle, 2019).

The feedback can be, for example, in the form of force, where the whole controller or some part of it pushes back to the user's hand or rumble of the controller to indicate contact with some solid material.

The type of controller is also important – using a stick-like controller is easy, but for some applications, like pilot training – to control the virtual control panel by his own hands is pivotal for learning to control the machine in the same way he really flies with it.

This section will cover all hand-based tracking types and their main representatives, from devices that simulate virtual keyboards and mice to sensors that display real-life users' hands and their movements in the virtual environment. Some of the devices try to be multi-purpose to cover most use-cases, but some are made for specialized use-cases, like text-input.

The main categories are **hand-held controllers**, where the user holds some device to track his hand movements and finger inputs. **Hand motion tracking** tracks the hand and finger movements directly, without any additional hand-held device. **Wearable hand tracking** is clothing that the user wears to provide the tracking. These categories are just subcategories of so-called ungrounded devices that are attached, held or worn on the human body, as opposed to grounded devices, fixed to the environment, e.g., desk mounted.

Grounded controllers (targeting non-VR applications, like a mouse, keyboard or joystick, or made for VR, like **PHANTOM** (1994) (Massie & Salisbury, 1994) or **HIRO** (2011) (Endo et al., 2011) can also be used to control the virtual environment, but with a very limited feeling of immersion for the user, because they do not provide free movement, thus they will not be discussed here. However, there are attempts to clone physical keyboard to the virtual environment by mixed reality modules (J.-W. Lin et al., 2017), as well as to create mouse-like controllers, providing 6 DOF, for example, **Space Ball 5000** (2003) (Virtual Realities, 2020) in figure 8 or **Cyberman** (1997) (Computing history, 2020).

4.1 Hand-Held Controllers

Physical controllers are the primary type of hand-controllers for virtual reality because they are the closest to the input tools we have used in the past. At the same time, interaction with the use of human hands was proved to be the most intuitive when compared to any other organ (Karam, 2006). After years

Figure 8 SpaceBall 5000 (Microsoft, 2020b)

of using a mouse, keyboard or joystick, people got used to working with some device that helps them to transfer their intentions to the virtual world (whether presented on a simple computer display, or in a more immersive fashion, like in VR).

The most straightforward division of handheld controllers is into **unimanual** (controllers that are used with one hand) and **bimanual** (controllers that are used with both hands). This corresponds with the research of human labour, where human actions can be divided in the same manner (Guiard, 2013). Some bimanual controllers consist of two identical unimanual controllers that enable users to do more complex actions (e. g. handle a bow and arrow). These controllers can, in some cases, be used as unimanual (the second controller is not used), but it lacks the advantages of bimanual work.

More advanced controllers provide haptic feedback (so the virtual world can give some cues about the user's contact with an object, e.g., when the user touches a wall). Vibrations of the controller provide the most common and the most simple form of feedback. More complex feedback can be made by force feedback of only parts of the controller in one direction (D. Chen & Chossat, 2019). Some handheld devices also try to guide users motion (physiologically cue either what movement the user should do next or provide motion feedback), but they are not common, and they are often not used for controlling the environment; they just provide the feedback (Walker et al., 2019).

Handheld controllers typically have buttons on the controller to provide inputs for selection or other simple forms of interactions. 2D joysticks are also often present.

4.1.1 Unimanual

Unimanual handheld controllers are often simple devices, typically in the form of a wand, that the user holds in one hand to control the virtual environment. They are easy to use; however, they do not support more complex interactions, because the user cannot use both hands, even though it is more natural for most actions (Guiard, 2013).

Most unimanual controllers are made for simple tasks like pointing, selecting an object or teleportation in the virtual environment.

CLAW (2018) (Choi et al., 2018), made by a collaboration of Microsoft Research and Stanford University, provides three distinct interaction styles – grasping a virtual object, touching virtual surfaces, and triggering. According to the way the user holds the controller, it changes the corresponding haptic rendering (see the device on figure 9). Servo motor, together with a force sensor, provides a force to the index finger when touching and grasping control style is used. Other haptic feedback methods are provided by vibrations and force feedback in a gun-like fashion. 6DOF is provided by the HTC Vive tracker mounted on the bottom of the device. However, this device is not wireless (it needs a power cord and USB cable connected) and, at this time, is only in a right-hand variant.

Figure 9 Microsoft's CLAW (Choi et al., 2018)

Another controller made by Microsoft, this time in collaboration with the University of Washington, is called **Haptic revolver** (2018) (Whitmire et al., 2018). This multipurpose controller provides touch, shear, texture and shape rendering by a revolving wheel that has various surfaces on the side (see figure 10). The controller detects the surface in the virtual world and selects wheel's surface accordingly (e.g., the user will feel a different surface for a table and a poker chip on the table). The wheel can also move up and down, providing pressure on the finger when needed. By spinning the wheel, the user can feel as he slides on the surface. The surfaces are reconfigurable by changing the wheel; even wheels with electronic components (like buttons or knobs) can be used. A single thumb button is used for selection. 6DOF is provided by the HTC Vive tracker mounted on the bottom of the device. However, this device is also not wireless (it needs a power cord and USB cable connected).

Figure 10 Microsoft's Haptic revolver (Whitmire et al., 2018)

ART, apart from positional tracking, created their own controller called **Flystick** (2011) (ART, 2020c) that uses an analogue 2D joystick and four buttons (three on the top and one trigger button) to interact. It can be used only with ART products, and it is tracked by passive markers. A similar wand was presented by WorldViz, called **PPT Wand** (2013) (WorldViz, 2020c), that cooperates with their PPT tracking system (see 3.1.1).

Researchers from Duke University presented **PhonePoint Pen** (2011) (Agrawal et al., 2011) system, where they use a cellphone as a pen to write with – by reading the cellphone's internal accelerometer, they recognize human writing. However, the system was made just for words or short notes, not for long sentences.

Some controllers are shaped liked a gun, and they are targeted for the gaming industry, like **VR Gun Controller** (2019) (Rahimi et al., 2019).

Other controllers, like Samsung's **Gear VR** (2015) (Samsung, 2020) or **Daydream controller** (2016) (Google, 2020b) are similar to TV remote controls – they are just a stick with buttons or trackpad, without haptic feedback. From these two devices, only Daydream controller has positional tracking.

Controllers resembling pens are also available. Logitech's **VR Ink** (Logitech, 2020) provides interactions in 2D or 3D environments, tracked by HTC Lighthouse 3.1.2, with additional input via buttons and force-sensitive controls. A prototype of another pen for VR was called **Light Chisel** (2015) (Bubnik & Havran, 2015), where a cylinder on the top of the device was illuminated with two LEDs and tracked by two cameras. A special spiral on the cylinder allows determining the device's rotation, allowing the device to be used as a screwdriver. See the device in figure 11.

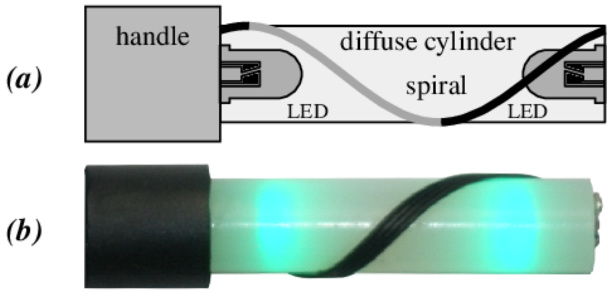

Figure 11 Tip of the Light Chisel
(a) Tip geometry,
(b) Photograph of the Light Chisel tip, light on. (Bubnik & Havran, 2015)

4.1.2 Bimanual

Bimanual controllers are either one device that is supposed to be held in both hands simultaneously or two identical devices, each held in one hand. The first approach is often used for more complex devices that have more buttons and triggers; the latter utilizes simpler devices but is based on the cooperation of both hands (e.g., button pressed on a device held in non-dominant hand opens a menu and dominant hand device is then used for selection of the menu item).

Researchers from École Polytechnique de Montréal found out that the use of both hands during a user interaction allows one to benefit from better feedback provided by the proprioceptive sense, making the interaction easier and more swift than with just a unimanual controller (for example, computer mouse) (Bernatchez & Jean-Marc, 2007).

Probably the most used controller for VR is HTC's **Vive Controller** (2015) (Steam, 2020) with 24 infrared sensors providing various input methods (trackpad, grip buttons, and a dual-stage trigger). The controllers are tracked by HTC Lighthouse (see 3.1.2) positional tracking and work wirelessly with the battery holding charge for 6 hours of operation time. Vibrations of the device provide haptic feedback. The controller can also be used in a unimanual fashion (when only one controller is needed). In 2019, Valve released their new headset, Valve Index, with **Valve Index** (VIVE, 2020) controllers. Valve Index has 87 sensors tracked by HTC Lighthouse and support finger-tracking and provide buttons and trackpads for additional input. See the device in figure 12.

Figure 12 HTC Vive controller (nicepng, 2020)

Oculus has its own **Oculus Touch controllers** (2016) (Oculus, 2020c) that have both index and middle finger trigger, as well as two buttons and a thumbstick (small joystick for the thumb) on the top of the controller, that can also detect if the finger is touching them or not (and display the position of the thumb in VR). The device can be seen in figure 13. The controllers are wirelessly connected to the headset, and they project an IR light that is tracked by the Constellation system (see 3.1.1), but the headset cannot track the controller behind the user. That is why Oculus sells an additional sensor that can be placed behind the user. (IGN, 2016)

Microsoft has a controller with a design very similar to Oculus Touch controllers – **Windows Mixed reality motion controller** (2017) (Support, 2020). It is in the form of a stick with a ring on the top. The ring has light emitters that provide optical tracking. The controller also has one button, thumbstick, touchpad and a trigger. Another Microsoft controller for their headset is very simple, it is

Figure 13 Oculus Touch controllers (Grover, 2020)

called **HoloLens Clicker** (2016) (Microsoft, 2020c), and it is just a small finger device that allows to click and scroll.

PlayStation VR has two controllers that differ only in design. **PlayStation Move** (2010) (PlayStation, 2020c) is made by two small sticks with a bulb on the top that emits the light that is tracked. The classic four PlayStation buttons (cross, triangle, cube and ring) are on the side. **PlayStation Aim** (2017) (PlayStation, 2020b) is made for computer games based on shooting – it is designed as a simple two-hand held weapon, with a thumbstick for both thumbs and with trigger for one hand and directional keys for the other.

The third controller created by Microsoft in recent years, **Haptic Links** (2018) (Strasnick et al., 2018), was created together with Stanford University. This controller addresses the problem of bimanual interaction. Most VR controllers utilize only one hand to manipulate objects in the virtual environment, and the ones that use both hands do not link the two-hand movements together, as seen in figure 14. Haptic Links creates a physical link from one hand to another to render forces between them. The controllers provide locking in an arbitrary configuration, constrain specific degrees of freedom or directions of motion, and dynamically set stiffness along a continuous range to make the interaction more life-like (for example, when the user drives with a steering wheel or plays virtual golf).

Tactical Haptics created **Reactive Grip** controller (2019) (Tactical Haptics, 2020) that consists of two parts that can be either held separately or connected by built-in magnets. This way, the parts can be put together to create various devices and guns. The controllers provide several buttons and triggers as the measn of input, and shear feedback is provided via sliding panels on the device.

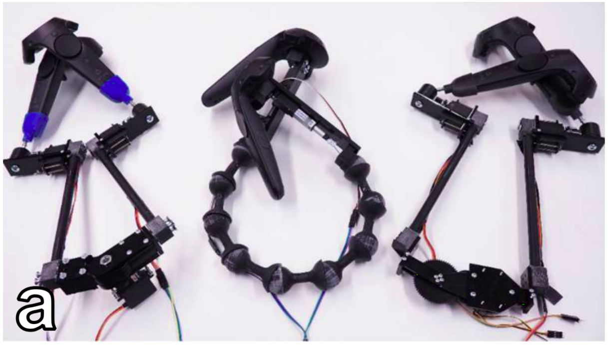

Figure 14 Haptic links (Strasnick et al., 2018)

Razer's collaboration with Sixense, the company that created STEM tracking (see 3.2.2), produced **Razer Hydra** (2011) (Razer, 2020), the most known controller that uses magnetic field tracking. It consists of a weak magnetic field source, controllers with five buttons, a thumbstick on the top, and two triggers on the front. It is made for computer games and has a very small range (not even a meter), so it significantly restricts the user's ability to move freely.

Sixense then created their own wireless **STEM controllers** (2014) (Adam Savage's Tested, 2014) based on the same technology as Razer Hydra, but this time the tracking range is about 2.5 meters. The tracking modules are not directly built into the controller, so it creates a possibility to make new controllers with a special design that integrates the tracker.

Etee (2020) (M. Lin, 2020) is presented as a button-free controller – the device utilizes proximity sensors to detect fingers, and that way can transfer full finger movement to the virtual environment. No buttons or thumbsticks are used for input – it is provided simply by touch, gesture, pressure and proximity of the finger to the controller, as seen in figure 15. HTC Vive trackers are used for positional tracking.

Similar to Etee, Samsung's **Rink** (2016) (Statt, 2016), a prototype of controllers for mobile-based headset GearVR, was presented. The controller is also based on proximity; however, the prototype was in an early stage of development, and no new information is available as of October 2021.

Finch Shift (2017) (Finch, 2020) puts two armbands (FinchTrackers) on the user's arms. It combines information from IMU units from the gloves, armbands and headset to triangulate each others position, thus providing 6 DOF without any other external sensor (Greenwald, 2019).

Figure 15 Etee button-free device (VR gear, 2020)

As with unimanual controllers, some bimanual controllers are again targeting the gaming industry and come in a shape of a gun, like Striker VR's **Arena Infinity** (2017) (Striker VR, 2020) or Ilium VR's **Athena Rifle** (2016) (Carbotte, 2016).

4.2 Hand Motion Tracking

Hand motion tracking refers to tracking the user's hands and fingers without any device that the user has to hold or wear. This approach is the most natural for users because they can use their hands the same way as in real life, without handling any device. This enables them to grab, carry and throw objects, open doors, or interact with other virtual environment representatives of the real-world devices, like press buttons or turn knobs.

The drawback is that without a controller directly placed on or in the user's hands, there are fewer possibilities to provide feedback to his actions. This can be compensated by, for example, acoustic feedback from a tracking pad. Another drawback is the occlusion of hands – when one gets in the way of the tracking signal between the source and the other hand, it breaks the tracking signal, and the hand detection is lost. The occlusion problem can also appear when fingers are tracked because they can be hidden behind each other or behind the hand itself. This can be compensated by having more than one tracking source (e.g., two infrared cameras) that send the signal from different angles. However, this approach brings yet another disadvantage. In some cases, it can be hard to have more sensors attached, so it does limit the user's view and his movement, and at the same time, place the trackers in different angles to the base tracker. For example, with a tracker placed directly into/onto HMD, finding the right place for an additional tracker can be very hard.

Optical hand motion tracking is based on the same principle as optical positional tracking (see 3.1. A camera tracks users' movements according to pattern recognition captured by visible light spectrum cameras or infrared signal captured by infrared cameras. This approach is the commercially most successful for hand tracking.

4.2.1 Optical Tracking

Leap Motion (first version released in 2013, version 2 released in 2014, in 2019 acquired by Ultrahaptic to create Ultraleap) (Ultraleap, 2020a) is the most known hand tracking controller on the market. It uses two IR cameras that track the user's fingers and hands by computing distortion of the IR grid created by a sensor. It also provides a simple API with information about the palm, fingers and joints. Visualizer of the hands is also included in the provided software. After being acquired by Ultrahaptic, the Leap Motion controller can be accompanied by a pad called Stratos, which sends acoustic signals that provide feedback for the hand and the fingers. (Ultraleap, 2020b) Leap Motion sensor can be seen in figure 16.

Figure 16 Leap Motion hand tracking (Ergürel, 2017)

In 2016, uSens presented **Fingo** (uSens Inc., 2016), their hand tracking system that uses IR grid technology. The system can be used as a standalone module or directly integrated into HMD. Apart from inside-out hand tracking, it also provides 6DOF positional tracking. Some modules, like PowerFingo, can also be used as an AR module. As with LeapMotion, a hand visualizer is provided.

Nintendo Wii Remote's controller (2010) (Nintendo, 2020) also used optical tracking – a bar with infrared lights is placed in front of the screen, and the controller computes the distance from the bar. However, Nintendo Wii is no longer in production.

Researchers from the University of Wisconsin-Madison created **Okuli** (2015) (Zhang et al., 2015) – a system for tracking users' fingers using visible light (a low-power LED and two light sensors) by emitting light on the workspace and collecting its reflection. The system was designed as an Android peripheral and achieved around one-centimeter precision.

4.2.2 Magnetic Field Tracking

Magnetic field tracking for hand and finger motion utilizes magnetic field generators in the same way as positional magnetic field tracking (see 3.2.2). The generators create the magnetic field that bounces back from the hand/fingers and is then processed by the source to calculate the hand's position. However, this approach is not as precise as other hand tracking systems, with most devices providing accuracy around a few centimeters. With positional tracking, a centimeter error does not have to be taken into account, but it can be crucial with finger tracking.

mTrack (2015) (Wei & Zhang, 2015) uses highly directional 60 GHz millimeter radio waves to track the movement of the user's finger. It also suppresses interference from background reflection. On a short range, the accuracy is less than 8 millimeters. The system is made for short-range finger tracking (like wireless transcription or virtual trackpads).

RF-IDraw (2014) (Wang et al., 2014) puts RFID on the user's finger to be able to track it with an accuracy of 3.7 cm only with long-range antennas.

Another prototype that uses magnets to track users' fingers is **Finexus** (2016) (K.-Y. Chen et al., 2016). The system places electromagnets on three fingernails of the user and tracks them with four sensors, as seen in figure 17. However, the sensors have to be in a distance of at least twelve centimeters from the tracked object to work.

4.2.3 Acoustic Tracking

Hand tracking based on an acoustic principle utilizes sound waves to determine the position of the hands and fingers, as well as it did with the whole user body (see 3.2.3). The Source of the sound signal

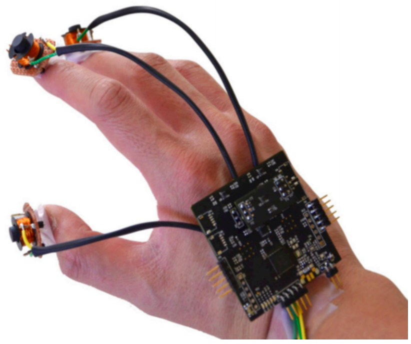

Figure 17 Finexus – magnetic field tracking prototype (K.-Y. Chen et al., 2016)

generates waves reflected and captured by a receiver, which determines the hand's position, mainly with Doppler shift calculation or sound signals phase changes.

HTC Vive Focus (2019) (Valve, 2020a) is the first commercial VR solution that utilizes acoustic tracking. The tracking is currently only used for hand controllers, not for the headset itself. In the headset is a sonar that transmits ultrasonic pulses that the controller processes and the data is combined with internal IMU units in the controllers to provide 6 DOF tracking. (Lang, 2018)

CAT: High-Precision Acoustic Motion Tracking (2016) (Mao et al., 2016) or **Accurate Air Mouse** (AAMouse) (2015) (Yun et al., 2015) by researchers from The University of Texas at Austin has speakers as a source and a microphone on a cellphone as a receiver. They combine distributed frequency modulated continuous waveform with Doppler shifts to achieve better precision. Thanks to that, they achieve a 9 mm tracking error in VR setup with three speakers.

Same with this technique is **BeepBeep** (2007) (Peng et al., 2007) with two centimeters accuracy over the distance of ten meters.

FingerIO (2016) (Nandakumar et al., 2016) specializes in tracking fingers around a cellphone. The device sends inaudible sound signals and tracks the echoes of the fingers at its microphone. With that, they achieved 2-D finger tracking with an average accuracy of 8 mm. However, the system is not made for VR, just for AR.

4.2.4 Others

In 2015, Google presented **Project Soli** (ATAP Google, 2020), a motion tracking system based on radar technology. The chip tracks movement from all angles and can detect hand and body poses as well as hand and finger gestures. Even though the initial applications were smartphones and smartwatches, Soli can be embedded in most wearables and electronic devices.

4.3 Wearable Hand Tracking

With the rising necessity to be able to move when exploring the virtual environment, controllers worn on the user's body are on the rise, as well as the need to track the motion of hands without carrying a controller. Wearable hand motion trackers combine the best of both worlds from hand motion tracking and handheld controllers. Like motion tracking, they provide deviceless interaction, where the user does not have to hold any controller. Like handheld controllers, they can provide tracking without occlusion of hands or fingers, and they also support haptic feedback.

Wearable hand tracking systems contain a set of sensors that determine the position of the hand and fingers, as well as their flexion (Temoche et al., 2012). The advantage of this approach is that the sensors are not affected by the environment (there is no occlusion of the tracking). There is a high recognition accuracy because the hands and fingers are tracked directly. However, wearable hand tracking systems are often more expensive because of the complex technology used, and they have to be calibrated frequently. (Y. Li et al., 2019)

Wearables are often categorized by the technology used for tracking and finger bending, but with the newest additions to the controllers' list that use more than one approach, the division becomes somewhat blurred. That is why we will divide wearables into three groups. The first group is **Lycra data gloves** that use lightweight lycra gloves with sensors that the user wears on his hand. The second group consists of **lightweight exoskeletons** made by a simple processing box placed on the back of user's palm, with cables connecting small sensors placed on the fingers. The last group is **hard exoskeletons** that are made from more rigid materials and can often be similar to artificial hands. **Other** wearable hand and finger tracking devices are usually put just on the tip of the user's finger(s).

The measurement of finger flexion is done with the help of fibre-optic sensors, foil-strain technology or resistive sensors. (Mazuryk & Gervautz, 1999) Others, not so common approaches, use microfluid processing or image processing.

Most wearable hand tracking systems provide only tracking of the hand and finger movement, and positional tracking has to be provided by some third-party positional tracking, most often HTC Vive tracking (see 3.1.2).

4.3.1 Lycra Data Gloves

Data gloves (sometimes also called haptic gloves) are often lightweight devices made of elastic materials with built-in sensors. This approach provides a tracking solution that the users are familiar with from their day-to-day life and have no problems wearing it, as well as being very straightforward when usability is concerned; thus, the learning curve is very steep.

However, the hands can sweat underneath the gloves, and some people can even have a rash from the material. Also, data gloves often do not provide the accuracy needed for some action, where extreme precision is needed (e.g., teleoperation or surgery) (Mazuryk & Gervautz, 1999).

One of the oldest haptic gloves, **VPL DataGlove** (Encyclopaedia Britannica, 2020), brought to the market in 1987, used fibre-optic sensors in the glove, which allowed computers to measure finger and thumb bending, thus providing information about gestures (CourseHero, 2020). The tracking was made by Polhemus tracking system (see 3.2.2) (Lasko-Harvill et al., 1988). Two years later, Nintendo released **Power Glove** (1989) (CourseHero, 2020), based on ultrasonic sensors, that measured the wrist position relative to the PC screen. Flex sensors were used to measure finger bending, and a keyboard placed directly on the glove was used for additional input, as seen in figure 18. The Power Glove was discontinued after one year.

CyberGlove System LLC has been creating data gloves since the 1990s, with their most successful product, the **CyberGlove** series (CyberGlove III was released in 2012) (Cyberglove Systems, 2020), data glove for motion capture, as well their other brands like **CyberTouch** or **CyberGrasp**, but no new information or product has been released in almost ten years.

Manus VR has several brands of haptic gloves. The newest addition, **Prime Haptic** (2019) (Manus VR, 2020), are lightweight lycra gloves that can track fingers, palms and wrists with 12 sensors wirelessly.

Figure 18 Nintendo's Power Glove (James, 2016)

The device can be seen in figure 19. The gloves use HTC Vive trackers for positional tracking. However, the company also released special gloves **Prime Xsens** (2019), in collaboration with Xsense (see 5.3), made for integration into Xsens motion capture suit. In 2021 Manus released **OptiTrack gloves**, which are made in collaboration with OptiTrack (see 3.1.1), and combine three technologies for finger tracking – OptiTrack tracking, integrated Manus sensors and two IMUs.

Figure 19 Manus VR Prime Haptic glove (Manus VR, 2020)

Fingertip-less gloves called **Senso** (2016) (Senso, 2020) promise precise hand and finger tracking with seven IMU sensors with haptic feedback for every finger, with five vibration motors. The battery is said to last for 10 hours. Optional positional tracking is made by HTC Vive by sensors integrated into the glove tracking module. The gloves can be combined with the whole body tracking called Senso suit (see 5.3).

Avatar VR (2017) (Avatar VR, 2020) provides wireless gloves with seven IMU and one flex sensor integrated directly in the glove, with possible two detachable IMUs for wrist and arm tracking. On the palm, thumb, index and middle fingers are also configurable conductive fabric zones, which can provide additional input, according to the settings made by the user. Haptic feedback is possible through 10 customized vibration actuators. The tracking is provided by the HTC Vive tracker.

CaptoGlove (2017) (CaptoGlove, 2020) provides tracking for all five fingers with lycra wireless glove, with one pressure sensor for the thumb.

Noitom's **Hi5** (2018) (Noitom, 2020b) uses fingertip-less gloves with a box containing AA batteries at the back of the user's palm. The gloves have six IMU sensors on each finger, and rumblers on the wrists provide haptic feedback. The gloves use HTC Vive trackers to determine position. However, the gloves are said to get magnetized by almost any kind of technology. This results in the need to recalibrate (Strange Reality Studios, 2019), because magnetization changes the tracking capabilities of the gloves.

VRfree gloves (2020) (Sensoryx, 2020) are wireless gloves where the user has to have a head-mounted sensor (clip-on for HMD) to track the gloves. The system promises to track the hands beyond the user's field of view and support multi-user collaboration.

VRgluv (2018) (VRGluv, 2020) are wireless gloves that connect to the computer via Bluetooth and provides force haptic feedback. With five sensors for each finger, the glove promises great accuracy, and it is said to provide the feeling of texture and shape of a virtual object. Positional tracking can be provided by any tracking device, like the HTC Vive tracker.

In late 2020, Rokoko released **Smartgloves** (Rokoko, 2020a), which contains 7 sensors per glove and are tracked by Wi-Fi up to 100 meters. Because the gloves do not include magnetometers, they are immune to magnetic distortions.

Omni company presented **Hands Omni** in 2015 (HaptX, 2015), wireless haptic gloves in a very early stage of development. The gloves provide feedback by inflating bladders with air underneath the user's fingers, providing various pressure forces. However, no new information was released as of October 2021.

Glove Touch (N/A) (Go Touch VR, 2020a) system is based on VRTouch finger tracking technology (see 4.3.4). This product can be used with any other glove on the market by integrating the VRTouch haptics into the glove. The device can be seen in figure 20.

Figure 20 GloveTouch with VRTouch technology (Go Touch VR, 2020a)

In 2017, Facebook patented **the Skin stretch instrument** (Facebook Technologies LLC, 2017), that can stretch the user's skin on his hands and fingers according to the object that the user holds. In October 2021, no device based on this patent was officially presented. The same concept was presented as **FinGAR** (2017) (Yem & Kajimoto, 2017) by researchers from The University of Electro-Communications, Tokyo.

4.3.2 Lightweight Exoskeleton Gloves

The design of the lightweight exoskeleton gloves is somewhere between data gloves and hard exoskeletons – it consists only of a small tracking box placed on the back of the user's palm, with strings, cables or elastic bands connecting the box and the tracking. These connectors cannot only do the finger tracking but can also provide force feedback by pull force provided by servo motors in the tracking box.

This approach can be more comfortable for the user because only part of the hand is covered. However, lightweight exoskeletons often do not track all fingers, and only some of them provide haptic feedback.

Force-feedback glove **The Rutgers Master II** (2002) (Bouzit et al., 2002) was presented as a prototype that placed rings on four user's fingers; those rings were connected to a motor that was able to provide force feedback up to 16 newtons from the centre of the user's palm. This also meant that the user could not use the hand as usual because the machine was always blocking his grip.

Finch (2016) (XinReality, 2020e) was supposed to be a simple haptic glove that used three user's fingers for interaction. The glove consists of a box with a sensor on the back of the user's palm connected to three sensors on the finger and one sensor on the arm. The system is connected wirelessly via Bluetooth to the computer. On the top of the index finger, there is a touchpad that enables additional input. By October 2021, no new information was available; the company supposedly shifted their attention to FinchShift handheld controller (see 4.1.2).

In 2018, BeBop Sensors announced **Forte Data gloves** (BeBop Sensors, 2020), which provides a lightweight, breathable design, because fingertips are connected to a sensor on the back of a user's palm only with belts, which also provide force feedback.

Plexus created their own **Plexus Haptic gloves** (2018) (Plexus, 2020), that is similar to Forte Data gloves, being just a sensor on the back of the palm connected to fingertips via rubber bands, as seen in figure 21. The gloves track not only every finger but every finger joint, with five tactile actuators for each finger.

Figure 21 Plexus lightweight exoskeleton data glove (Plexus, 2020)

BreqLabs created **ExoGlove** (2015) (Breq Labs, 2020) that consists of five rings placed on each of the user's fingers, connected to a box on the back of the user's palm. The hand device is tracked by ultrasonic waves by the receiver placed on the headset.

ART also produces its own hand tracking, **Fingertracking** (2015) (ART, 2015), where they put a device to the back of the user's palm, which is connected to the user's fingertips (they have three-finger and five-finger versions), but no haptic feedback is provided, as displayed in figure 22. The system is then tracked with ART positional tracking technology (see 3.1.1).

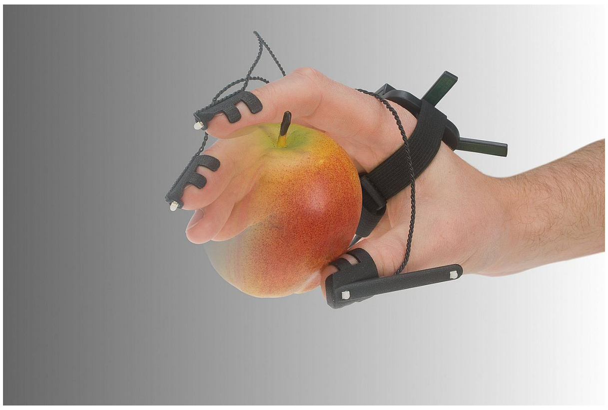

Figure 22 ART Fingertracking (ART, 2015)

Japanese company Exiii created **EXOS Wrist** (DK2 released in 2018) (Exiii, 2020), a wrist-strapped device that provides counter-force feedback in two directions – palm up and down and left and right. The device itself is not a controller; however, it can be accompanied by regular controllers, like EXOS Gripper, handheld controller, or any other controller on the market. The positional tracking can be provided by placing HTC Vive on the wristband.

4.3.3 Hard Exoskeleton Gloves

Hard exoskeletons provide a rigid, futuristic design that can give the impression that the user has an artificial limb. The rigid design makes it heavier than the data gloves, but it helps to provide more accurate finger tracking. Older hand tracking systems with hard exoskeletons are often called dextrous manipulators, thanks to their ability to provide more precise finger-movement data (Mazuryk & Gervautz, 1999).

One of the first dextrous machines was a force-reflecting glove, the **LRP-Dextrous Hand Master** (DHM, released in 1997) (Tzafestas & Coiffet, 1997). DHM consisted of an exoskeleton structure and several tendons connected on the top of each finger segment. It provides force feedback on each hand segment and can measure the angle of 14 finger joints, as seen in figure 23.

Novint XIO (2011) (Novint Technologies, 2020) is a controller for both hand and arm, thus providing feedback for the whole limb. The last information about this device was that it is in a prototype stage, and ten years later, in 2021, no new information is available.

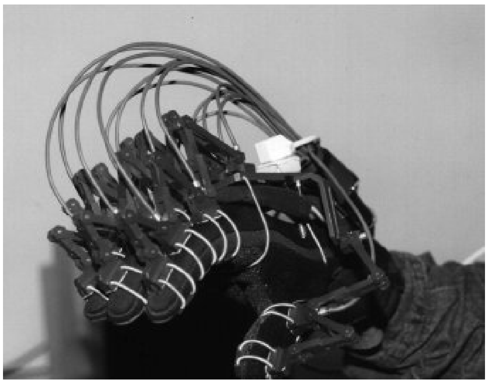

Figure 23 LRP-Dextrous Hand Master (Tzafestas & Coiffet, 1997)

In 2016, HaptX company filed a patent (HaptX, 2016) for whole-body human-computer interface based on microfluid processing, enabling the user to feel shape, movement, texture, and weight of virtual objects. the microfluid skin is made from flexible, silicone-based smart textile, which contains an array of high-displacement pneumatic actuators and microfluidic air channels. In 2018, **HaptX** gloves (HaptX, 2020) were released, which utilize this technology for hand-tracking. Each glove contains 130 microfluidic actuators. The actuators provide feedback by pushing against the user's skin the same way any real-world object would. The microfluid skin is only 1.5 millimeters thick. The glove is connected to an exoskeleton that provides force feedback to fingers to complement the immersiveness. The glove itself is tracked by a magnetic motion tracker.

Dexmo (2020) (DextaRobotics, 2020), presented as the world's first commercialized lightweight force feedback glove. Nevertheless, it is made of a hard exoskeleton connected to the user's palm and fingertips. Apart from haptic feedback via vibrations, it provides force feedback thanks to servo motors in the palm part that can stretch or extend the fingers.

A similar design will be used for **Teslasuit gloves** (2020) (Othanji, 2019), which can be used either as an add-on to a Teslasuit (see 5.1) or as a standalone controller, as seen in figure 24. It will provide a touch and texture effect for fingertips, as well as force and vibration feedback for fingers. It will also support biometry measurements, like measurements of impedance or pulse.

P5 Glove (2002) (Essential reality, 2020) used an exoskeleton glove tracked by optical tracking. The **5DT Data Glove Ultra** (2008) (5DT, 2020a), a fibre-optics based glove, was created in two versions. One had five built-in sensors and another with 14. The gloves are also available in a wired version that

Figure 24 Teslasuit hard exoskeleton gloves (Othanji, 2019)

uses a USB cable or wireless Bluetooth version. The glove was tracked by the 5DT ultrasonic tracking system (3.2.3).

4.3.4 Other

Wearable hand tracking solutions do not include only gloves and exoskeletons. Other approaches on the market are worth mentioning, even though they do not fall in the categories stated in the previous sections. In the recent decade, haptic devices that utilize only the user's fingertips are getting more popular.

These devices use just one part of the hand, like devices that consist of a module worn on the tip of the finger (sometimes more modules for more fingers can also be used), and provide not only motion tracking but various haptic feedback. Very few devices also use the user's arms to provide input by putting armbands on each arm, thus tracking the movement of the whole limb. These solutions, if not accompanied by hand tracking or other technology, do not provide finger tracking. Some devices are even made to be worn like a ring.

CyberTouch (2015) (S. Lee et al., 2015) puts bands on the user's forearms that provide positional tracking with two IMUs in the bands and finger tracking via EMG (Electromyograph) sensors. This provides enough data to enable a user interface that supports interactions like drag-and-drop, zooming or scrolling.

Tactai (2017) (Tactai, 2020) haptic device, even though it does not cover the whole hand, provides haptic feedback for a finger (or multiple fingers) by attaching a finger module to a fingertip, as displayed in figure 25. It can provide pressure, heat, surface and other feedbacks, like patterns or softness.

Figure 25 Tactai (Boston Voyager, 2018)

A similar approach is used by **VRTouch** (2017) (Go Touch VR, 2020b) by Go Touch VR, which puts sensor clipons on three users' fingers. However, this device only provides touch and vibration feedback. The tracking is done by internal IMU and integrated Leap Motion tracking (see 4.2.1), but any other tracking system can also be used. The system is integrated into their other product, GloveTouch (see 4.3.1); this time, it is directly a data glove.

In 2014, **the Myo armband** (Bernhardt, 2015) was released, which provided hand tracking via two armbands strapped on the user's arms. The armbands had nine built-in IMUs to track the movement of the arms and eight EMG (electromyography) sensors to read muscle movements and detect gestures. However, in 2018, the product was discontinued so that the company could focus on another product (Fingas, 2018). An armband called **Unlimited hand** (2015) (Unlimited Hand, 2020) also reads the user's muscle movements to detect hand and finger movements. It stimulates the user's muscles by electric impulses, thus moving his hands and fingers in the same manner it would move when the user touches an object.

Nod (2014) (Nod, 2020) is a ring meant to be worn on the user's finger that provides various buttons and a joystick to control the virtual environment. The device can be seen in figure 26. The same principle was used by **EasySMX Ring Mouse** (2019) (Daro, 2019).

Figure 26 Nod – a finger ring controller (Nod, 2020)

4.4 Summary

The following table is a summary of VR hand-based controllers. From every company, only one (the best) controller is stated.

Table 2: Summary of hand-based controllers

Name	**Freq.**	**Lat.**	**Acc.**	**# parts**	**# con.**	**Feedback**	**Range**	**Status**
CLAW	333	N/A	0.3	1	N/A	Yes	7	CU
Haptic Revolver	90	N/A	0.3	1	N/A	Yes	7	CU
ART Flystick 3	N/A	N/A	N/A	1	4	No	4.5	CU
PPT Integrated wand	N/A	N/A	N/A	1	1	No	4.5	CU
PhonePoint pen	N/A	N/A	N/A	1	1	No	N/A	PR
VR Gun Controller	N/A	N/A	N/A	1	1	Yes	N/A	PR
Gear VR controller	N/A	N/A	N/A	1	1	No	N/A	CU
Daydream Controller	N/A	N/A	N/A	1	1	No	N/A	CU
VR Ink	N/A	N/A	N/A	1	1	Yes	N/A	CU
HTC Vive Controller	250	50	0.3	2	unlim.	Yes	7	CU
Oculus Touch	60	N/A	N/A	2	N/A	Yes	N/A	CU
Windows mixed reality con.	N/A	N/A	N/A	2	N/A	No	N/A	CU
Hololens Clicker	N/A	N/A	N/A	1	1	No	N/A	CU
Playstation Move/Aim	N/A	N/A	N/A	2	N/A	No	4.6	CU
Haptic Links	N/A	N/A	N/A	1	N/A	Yes	N/A	PR

Table 2: Summary of hand-based controllers

Name	Freq.	Lat.	Acc.	# parts	# con.	Feedback	Range	Status
Reactive Grip	N/A	N/A	N/A	2	2	Yes	N/A	CU
Razer Hydra	N/A	N/A	1	2	2	No	0.9	NFS
STEM controller	250	N/A	N/A	2	5	No	2.5	CU
Etee	250	15	0.3	2	2	Yes	7	NYR
Rink	N/A	N/A	N/A	2	N/A	No	N/A	PR
FinchShift	100	27	N/A	2	2	No	N/A	CU
Arena Infinity	N/A	N/A	N/A	1	25	Yes	10	CU
Athena Rifle	N/A	N/A	N/A	1	1	Yes	N/A	CU
LeapMotion	240	8	N/A	1	1	Yes	0.8	CU
Fingo	N/A	N/A	N/A	1	1	No	N/A	CU
Nintendo Wii Remote	N/A	N/A	N/A	1	1	Yes	10	NFS
Okuli	30	15	N/A	1	N/A	No	N/A	PR
mTrack	N/A	N/A	8	1	N/A	No	N/A	PR
RF-IDraw	N/A	N/A	37	1	1	No	N/A	PR
Finexus	N/A	N/A	1.33	2	1	No	0.12	PR
HTC Vive Focus	N/A	N/A	N/A	2	2	Yes	N/A	CU
CAT	N/A	N/A	9	1	N/A	No	N/A	PR
AAMouse	200	40	14	1	N/A	No	4	PR
BeepBeep	N/A	50	20	1	1	No	10	PR
FingerIO	N/A	N/A	8	1	1	No	<1	PR
Soli	N/A	N/A	N/A	1	N/A	No	N/A	PR
VPL DataGlove	N/A	N/A	N/A	2	N/A	No	N/A	NFS
Power Glove	N/A	N/A	N/A	2	N/A	No	N/A	NFS
CyberGlove III	120	N/A	N/A	2	N/A	No	30	NFS
Prime Haptic	200	5	N/A	2	2	No	N/A	CU
Avatar VR	N/A	<15	N/A	2	2	Yes	N/A	CU

Table 2: Summary of hand-based controllers

Name	Freq.	Lat.	Acc.	# parts	# con.	Feedback	Range	Status
CaptoGlove	N/A	N/A	N/A	2	2	Yes	N/A	CU
Hi5	N/A	<5	N/A	2	2	Yes	N/A	CU
VRfree	120	N/A	N/A	2	2	No	N/A	CU
VRGluv	N/A	10	N/A	2	N/A	Yes	N/A	CU
Rokoko Smartgloves	400	20	N/A	2	N/A	No	100	CU
Hands Omni	N/A	N/A	N/A	2	2	Yes	N/A	PR
GloveTouch	N/A	N/A	N/A	2	N/A	Yes	N/A	CU
The Rutgers Master II	N/A	N/A	N/A	1	N/A	Yes	N/A	PR
Finch	100	7.5	N/A	1	N/A	No	N/A	NFS
Forte Data Gloves	N/A	N/A	N/A	2	2	Yes	N/A	CU
Plexus	180	N/A	N/A	2	2	Yes	N/A	CU
ExoGlove	90	<16	0.5	2	2	No	N/A	CU
ART Fingertracking	300	<20	N/A	2	2	No	4.5	CU
EXOS Wrist	N/A	N/A	N/A	2	2	Yes	N/A	CU
DHM	120	N/A	N/A	2	2	No	N/A	CU
Novint XIO	N/A	N/A	N/A	1	1	Yes	N/A	PR
HaptX	N/A	N/A	<1	2	2	Yes	N/A	CU
Dexmo	N/A	N/A	N/A	2	2	Yes	5	CU
Teslasuit gloves	N/A	N/A	N/A	2	2	Yes	N/A	CU
P5 Glove	N/A	N/A	N/A	2	2	No	N/A	NFS
5DT Data Glove Ultra 14	N/A	N/A	N/A	2	2	No	20	NFS
CyberTouch	N/A	N/A	N/A	2	2	No	N/A	PR
Tactai	N/A	N/A	N/A	1	2	No	N/A	CU
VR Touch	N/A	N/A	N/A	2	2	No	N/A	PR
Myo armband	N/A	N/A	N/A	2	N/A	No	N/A	NFS
Unlimited hand	N/A	N/A	N/A	1	N/A	Yes	N/A	CU

Table 2: Summary of hand-based controllers

Name	Freq.	Lat.	Acc.	# parts	# con.	Feedback	Range	Status
Nod	N/A	2	1	1	N/A	No	N/A	CU
EasySMX	N/A	N/A	N/A	N/A	N/A	No	N/A	CU

Freq. – reported data frequency in hertz

Lat. – latency in milliseconds

Acc. – accuracy in millimeters

 # parts – number of parts that the controller consists of

 # con. – the maximum number of controllers that can be used at the same time

Feedback – if the device has haptic feedback or not

Range – the range of the tracking in meters

Status – the status of the tracking (PR – prototype, CU – commercially used, NFS – not for sale, NYR – not yet released)

N/A – information could not be found

4.5 Discussion

Hand-based controllers are the most diverse type of controllers for VR. As you can see, many approaches for hand-based interactions arose in the last few decades, with some more successful than others. However, there is no clear winner that will dominate the market in the next few years.

Of course, the gaming industry will always have its favourites. For now, it is the HTC Vive controller, but it is because the gaming sphere can (and prefers to) survive without elaborate devices. Gamers just need some easy way to wield a gun, and that can be done with the stick-like easily without the need for interaction that is close to reality. The games are so immersive that pressing a button on a controller can feel like pulling a trigger without a great imagination.

On the other hand, industry, training and medicine are much more complex, and they provide a great deal of money for the research too. For them, sticks are not enough.

For industry and training, hand motion tracking presents a way to provide realistic interaction just with the use of cameras. The possibility to open the car door or turn a knob on the control panel just with bare hands allows the marketers to show the strength of their product. It does not matter if it is a virtual car or helicopter simulator. Here, the precision error of a few millimeters does not make such a difference.

The important interaction feedback for training can be provided by mixed reality – for example, the helicopter cockpit can be recreated both in the real and virtual world. The user sees the VR version but touches the real one. This allows a perfect immersivity that is needed for meaningful training.

The medical industry needs more precision and feedback than the rest. For this, the wearables are the best choice, even though they are not so comfortable to wear. Specialized controllers for surgeons will probably be more and more frequent in the upcoming years. However, they will most likely be grounded (e.g., mounted to a table) to provide the needed steadiness.

Again, as with positional tracking, acoustic and magnetic field tracking suffers too much from interference from other sources, so it is not as precise as optical tracking, so it is deemed unusable for hand tracking.

5 Body Tracking and Wearable Body Haptics

To provide the virtual world with a great deal of immersiveness, not only the use of users' hands and feet are essential. The ability to provide tracking of the whole body is not important only for motion capture, but it can move the immersivity of the virtual world to another level. Body tracking can provide a more precise position for the user's torso but also for their limbs. Another important aspect is the possibility to provide haptic feedback for the whole body, so the user can, for example, feel when he kicks a ball or is hit by a bullet.

Thus, the number of sensors, both haptic and tracking, plays a great role when immersivity and precision is concerned. With a large number of feedback modules, the device can provide targeted feedback (e.g., bullet hits a specific spot of the body) or cooperate on more complex patterns (e.g., when the user is cut by a knife, the pain can follow the movement of the knife).

With full-body tracking, another aspect of the virtual world can be utilized – the user's physical functions. With the body already covered in sensors, it is also to measure the heart rate, sweating or electrical current of the user's skin. This can give us important information about his fatigue or his enjoyment of the virtual world. Thanks to that, we can further evaluate the immersiveness and the selected technologies.

The devices can be divided into three main categories – **haptic suits** provide a wearable, full-body interface that the user puts on as any other piece of clothing, a **haptic vest** is a wearable interface for the torso that specializes in haptic feedback and **body sensors** are not made from one piece of cloth but are just sensors placed on the user's regular clothes.

5.1 Haptic Suits

Haptic suits are full-body suits that have integrated sensors for motion tracking. Some are worn on regular clothes as a second layer, and some are worn on a naked body – in this case, they usually have sensors to track bodily functions, like EEG or muscle movements. This way, they can also provide haptic feedback via electro stimuli. Another way to provide feedback for the user is through vibration actuators.

The suit has to be made from a material that the user can wear for a longer period of time and still feel comfortable. The suit also should not obstruct the user's movement in any way. The suit can consist of one full-body part or can be made out of several parts, like pants, vest and arms. Also, a lot of haptic suits can be accompanied by haptic gloves (see 4.3.1).

One of the first haptic suits was **VPL DataSuit** (1988) (Lasko-Harvill et al., 1988), that can be seen in figure 27. It was an addition to VPL DataGlove (see 4.3.1). The system was based on the same optical-fibre bend sensors, potentiometers, contact switches and Polhemus 3-Space Tracker sensors (see 3.2.2).

Figure 27 VPL Data suit (Zero, 2020)

HoloSuit Pro (2018) (HoloSuit, 2020) was one of the first full-body haptic suits that the public could buy. It provides 40 embedded sensors and nine haptic feedback devices dispersed across both arms, legs and all fingers and thumbs. It also provides six embedded buttons as input methods. The suit can be bought as a whole, but it can also be purchased as separate parts (jacket, pants, left and right gloves as well as head and foot extensions). It could be used for sports, healthcare, education, entertainment or industrial operations.

Rokoko's **Smartsuit Pro** (2017) (Rokoko, 2020b), previously known as Salto, provides a 1-part suit that does not need any other device to work. The suit creates its own Wi-Fi hotspot that can be connected to, and it sends the data via this connection. The user can set his body measurements (height, arm length, etc.) to make the tracking more precise.

Teslasuit (2018) (Teslasuit, 2020) is a suit filled with technology – but it does not only provide full-body tracking – it also has sensors that track vitals and emotional stress levels. It is supposed to be worn without any other layer of clothing underneath it, so the electrical signals can reach the nerve endings and provide a full-body haptic by electrical pulses via 80 channels. The suit connects to the computer by Wi-Fi or Bluetooth. The suit can be seen in figure 28.

bHaptic company has several devices from **TactSuit** (2017) (bHaptics, 2020) series – Tactot (haptic vest), Tactal (haptic cushion for face) and Tactosy (haptic sleeves for arms, haptic armour for hands and haptic socks for feet). Tracking is provided via the HTC Vive tracker.

Synesthesia Suit (2015) (Syneshesia Suit, 2020) is a full-body suit created specifically for the sound-based game Rez Infinite. It provides not only vibrational feedback but also sounds and colour to match the game, thus combining sight, sound and touch.

5.2 Haptic Vests

Most haptic vests are not controllers because they do not enable the user to provide any input, nor positional tracking or hand tracking (the only vest that does positional tracking is the Hardlight suit (see 5.2), but they are stated here for the completeness of the topic.

Haptic vests are made for providing feedback for the user via haptic feedback. The most common approaches use vibrations (by vibration actuators) or sound waves (by speakers or vibrating frames of the

Figure 28 Teslasuit (Teslasuit, 2020)

vest, transferring the vibrations to the body). Haptic vests are often made for gaming or other forms of entertainment.

In 2013, **ARAIG** (ARAIG, 2020) – As Real As It Gets vest started a funding project on Kickstarter, but it failed to raise the needed money. Nevertheless, after seven years, the community around the project is still active, and the creators report that they are still working on the west. With that being said, no device has been shown as of October 2021.

Hardlight Suit (2016) (Sinko, 2017), developed by NullSpace VR, provides a vest with haptic feedback not only for the torso but also for arms, by 16 vibration pads. It is also the only haptic vest that supports positional tracking (even though through third-party companies like HTC Vive and Oculus). Unfortunately, the project bankrupted in 2018.

High Fidelity (HighFidelity, 2020), creators of High Fidelity VR platform, partnered with NeoSensory (NeoSensory, 2020), a technology manufacturer, to create **Exoskin** (Koolonavich, 2018), vest with 32 sensory motors to provide haptic feedback, supposed to be released in 2018. However, in October 2021, no information about the product was available.

A very interesting approach to body haptics is made by Woojer's **Edge** (2019) (Woojer, 2020), which uses Woojer's patented oscillating frame actuators that generate sound waves to provide haptic for the user, as seen in figure 29. The frequency of the sound waves varies according to the needed feedback (the range is from 1 to 500 Hz). A similar approach is used by **KOR-FX** (2014) (KOR-FX, 2020), which also uses acusto-haptic technology to provide directed haptic feedback.

Figure 29 Woojer's Edge with its sound haptics points (Woojer, 2020)

Disney, in collaboration with MIT and Carnegie Mellon University, developed a prototype of a pneumatically-actuated haptic jacket called **Force Jacket** (2018) (Delazio et al., 2018). It provides force feedback by independently inflating and deflating 26 airbags, as well as vibration feedback for the torso. Carnegie Mellon University previously presented **PneuHaptic** (2015) (He et al., 2015), which provided a similar airbag system, but just as armbands. **3rd Space ballistic impact vest** (2007) (TN Games, 2020) also uses airbags for haptic feedback. This product is made for gaming and was commercially released. **Frozen Suit** (2017) (Maimani & Roudaut, 2017), presented by researchers for the University of Bristol, provides haptic feedback by stiffness patches on the user's body, which can block some parts' movement of the body in the desired direction.

Pakistani company Haptika works on **Haptika** vest (2015) (Pita, 2017) that enables users to feel the temperature of the virtual environment, but no information was available as of October 2021. For The Void (The Void, 2020), immersive virtual experience, **Rapture vest** (2016) (Pita, 2017) was created, which uses vibrations as haptic feedback.

5.3 Body Sensors

This approach places sensor modules on the user's body without any additional clothing layer; the sensors are placed on the top layer of the clothes. The placing of the sensors is more time-consuming than using a haptic suit, but it can be more comfortable for the users because they wear what they prefer.

The sensors can be connected by wires, or they can communicate wirelessly both with each other and the central processing hub. The fact that the sensors are placed and connected one by one makes this approach more flexible and scalable because, in theory, it is up to the user if he wants to use three sensors or hundreds of them. The user can sometimes also decide on what part of the body the sensors will be placed.

Perception Neuron Pro (2019) (Noitom, 2020a) consists of multiple interconnected IMU sensors (called neurons) placed on the user's body, as displayed in figure 30. The more neurons used, the more precise is the tracking. The number of the neurons can also define the body parts that will be tracked (e.g., from only right hand to full-body tracking). The data are then sent to the computer either by USB cable or over Wi-Fi.

Figure 30 Perception Neuron Pro (SusyNeuron, 2018)

Not yet released **PrioVR** (YostLabs, 2020) is made by a set of sensors connected wirelessly to a central hub on a user's back. Any tracking gloves can accompany the system.

Xsens created **MVN Analyze** (2019) (Xsens, 2020), body sensors that can be used both inside and outside and are made for a variety of fields of application, like human-machine interaction, sports or rehabilitation.

Sixense with their STEM positional tracking system (see 3.2.2) also provides something that they call **STEM Pack** (2014) (Adam Savage's Tested, 2014). In it they use their STEM tracking module, that works on the principle of magnetic field tracking, to track the human body. Two modules are also placed in the STEM controllers (see 4.1.2), one on each leg and one on the waist belt.

Senso, creator of Senso gloves (see 4.3.1), released **the Senso suit** in 2017 (Senso, 2020). It consists of 15 modules, each with its own IMU and vibration motor (for haptic feedback), which could be mounted on arms, legs and torso. The modules can be connected either with a USB cable or Wi-Fi. For even more precise tracking, HTC Vive positional tracking can be used, because there are sensors integrated into every module.

In 2020, Manus VR, which made its name for Prime Haptic data gloves (see 4.3.1), will release **Polygon**, a system consisting of five HTC Vive trackers (two on the data gloves), two on the user's feet and one on the waist. The Polygon software then computes the body and limbs position accordingly.

5.4 Summary

The following table is a summary of the full-body suits. From every company, only one (the best) suit is stated.

Table 3: Summary of full-body suits

Name	**Freq.**	**Lat.**	**# sensors**	**# parts**	**Feedback**	**Range**	**Status**
VPL DataSuit	60	N/A	N/A	3	No	4.5	NFS
HoloSuit Pro	N/A	N/A	40	7	Yes	N/A	CU
Rokoko Smartsuit Pro	100	90	19	1	Yes	100	CU
Teslasuit	300	10	10	1	Yes	N/A	CU
TactSuit	N/A	N/A	70	5	Yes	N/A	CU
Synesthesia suit	N/A	N/A	26	1	Yes	N/A	CU

Table 3: Summary of full-body suits

Name	**Freq.**	**Lat.**	**# sensors**	**# parts**	**Feedback**	**Range**	**Status**
ARAIG	N/A	N/A	N/A	1	Yes	N/A	PR
Hardlight Suit	N/A	N/A	16	1	Yes	N/A	NF S
Exoskin	N/A	N/A	32	1	Yes	N/A	NFS
Edge	250	N/A	8	1	Yes	N/A	CU
KOR-FX	N/A	N/A	N/A	3	Yes	N/A	CU
Force Jacket	N/A	N/A	N/A	1	Yes	N/A	PR
PneuHaptic	N/A	N/A	N/A	2	Yes	N/A	PR
3RD Space	N/A	N/A	8	1	Yes	N/A	CU
Frozen Suit	N/A	N/A	N/A	unl.	Yes	N/A	PR
Haptika	N/A	N/A	N/A	N/A	Yes	N/A	CU
Rapture vest	N/A	N/A	N/A	N/A	Yes	N/A	CU
Perception Neuron Pro	120	<20	32	32	No	N/A	CU
PrioVR	200	7	19	3	No	100	NYR
MVN Analyze	240	20	17	31	No	150	CU
STEM pack	250	N/A	5	5	No	2.5	CU
Senso Suit	N/A	N/A	15	15	Yes	N/A	CU
Polygon	N/A	N/A	5	5	No	N/A	NYR

Freq. – reported data frequency in hertz

Lat. – latency in milliseconds

 # sensors – number of sensors in the suit

 # parts – number of parts that the suits consists of (e. g. jacket, pants etc.)

Feedback – if the device has haptic feedback or not

Range – the range of the tracking in meters

Status – the status of the tracking (PR – prototype, CU – commercially used, NFS – not for sale, NYR – not yet released)

N/A – information could not be found

5.5 Discussion

Full-body suits are the least developed devices for VR. However, the rising need for immersivity will fasten their rise. Full-body suits will help us provide life-like virtual avatars and have the potential to push the positional tracking out of the focus of the industry, as well as the locomotion tracking.

If done well, they can measure the movement, position and physical functions of the user, as well as provide him feedback. The forms of feedback will also improve over time, and even multiple types can be combined to provide different sensations to the user.

This approach can change the VR interaction for good because it can replace several tracking approaches at once.

The full-body suits have more future than separate sensors because they are easier to wear, and this will be the dealbreaker that will decide the usefulness of these two approaches.

6 Gaze

One of the means of input that was neglected for a long time is eye-tracking. It can seem that the user's gaze cannot provide enough (relevant) information to control a virtual environment, but it can make the user's work easier when used correctly. Marc Bernatchez and Jean-Marc Robert discovered (Bernatchez & Jean-Marc, 2007) that tracking users' eyes and moving, for example, the program's menu accordingly, can drastically decrease the time needed to complete a task. However, studies showed that users do not prefer this frame of reference because they are not used to it. Yet.

Even if you do not change the frame of reference according to the user's gaze, the data can be used to highlight an object that the user looks at or even display a line that symbolizes the direction of the user's gaze.

The use of eye-tracking can be meaningful even for other parts of extended reality than the user interface. One of its core features is foveated rendering, which saves processing power. Eyes only process a small view area in high definition, so foveated rendering enables rendering only the part the user is focused on in high definition.

One of the most promising usages of eye-tracking can be even outside of the VR/AR field, and that is medicine. People that cannot move their hands (e.g., quadriplegics) or people who have had one or both of their upper limbs amputated could benefit significantly from using their eyes as the main means of input.

The eye-tracking technology is also linked to face and expression recognition technology that brings your emotions into the VR world. Companies like FACE (360 Channel, 2019) or Veeso (Futurism, 2016) provide these functions for several VR headsets. (hyprsense, 2017)

The eye-tracking systems can be split into three main categories according to the format of the device – **external devices**, **glasses** and **HMD integrated eye-tracking** – or three categories according to the used technology – **infrared sensors**, **image processing** or **electro-oculography**. Infrared technology is the most common for eye-tracking. Other approaches are represented only by a few devices, so they are summarized together in Section 6.2.

6.1 Infrared Sensors

Infrared sensor devices are based on infrared signal (pattern) sent from the device to the user's face, reflected from his eyes back to the device and processed accordingly. Two types of infrared sensors can be used – bright pupil tracking or dark pupil tracking.

Bright pupil eye tracking uses an illuminator placed close to the optical axis of the imaging device in the eye-tracker, causing the pupil to appear lit up. The illuminator is placed away from the optical axis with **dark pupil** eye tracking, causing the pupil to appear darker than the iris. (Tobii Pro, 2020a). Both are used for different light setting and different users (age or ethnicity can play a huge role). The tracker can also track one (monocular tracking) or both (binocular tracking) eyes of the user.

6.1.1 External

External eye-tracking devices (also called remote) are standalone devices that can be attached, for example, to the user's monitor and track the eyes without the need for the user to wear any device on his head, which can often be uncomfortable. The drawback of this approach is that the tracking is only available when the user looks in the direction of the tracker – there is not a possibility for the user to track his eyes during some work that requires him to turn or simply go away from the device. However, if it is used only for tracking eyes during user's work on a computer, it is the most comfortable technology, because it does not obstruct the user's line of sight.

One of the devices enabling the external tracking of user's eyes is **Tobii VR** (Tobii VR, 2019a) (newest device, Tobii Pro Fusion, released in 2019, can be seen in figure 31). It supports foveated rendering, and it can also use inter-pupillary distance to adapt the HMD to the current user's face to provide him the best experience. This goes hand-in-hand with user identification, that can set up user's preferences after identifying him with his eyes. When the software part is concerned, it improves user experience by allowing hand-eye coordination (the ability to coordinate hands according to information provided by sight), which combines the two inputs to ease, for example, picking up or throwing objects in virtual reality. Avatars in VR (virtual representations of the user) can also be more realistic when eyesight is used, which can help for multi-player environments or VR calls because it can show the real eye movement of the user. Tobii VR sells several types of devices – four are external devices with only slight changes in specifications. According to the current user and light settings, most of them can automatically switch from bright pupil tracking to dark pupil tracking. (Tobii VR, 2019b)

Figure 31 Tobii Pro Fusion (Tobii VR, 2019a)

The Eye Tribe Tracker by the Danish The Eye Tribe (The Eye Tribe, 2019) (2013) has a device that works just with Windows and Mac operating systems, but it can even be plugged into Android smartphones and tablets, thus enabling eye-tracking for a lot of devices that are neglected by the rest of eye-tracking companies. The company was bought by Oculus in 2016. (The Eye Tribe, 2016)

German company SensoMotoric Instruments (Wayback machine, 2018) has created several eye-tracking devices, one of which is **SMI RED500** (2014) – screen-based eye tracker with a 500 Hz refresh rate – but Apple Apple, Inc., 2019 later bought the company, and no new information about their products is available.

Arrington research provides multiple tracking systems, one of which, **400 Hz Binocular USB** (beginning of the 2010s) (Arrington Research, 2020a), promises 400 Hz tracking for one external camera that can be used with both dark and bright pupils, as well as in monocular or binocular version. The binocular version can be seen in figure 32. However, the user has to be at a specified distance from the tracker, and the distance is static (set during the first setup).

Figure 32 Arrington research's 400 Hz Binocular USB eye tracker (Arrington Research, 2020a)

Other companies providing external eye-tracking hardware are SR Research (SR Research, 2020a) (**EyeLink 1000 Plus**, released in 2017, that has frequency up to 2000 Hz and can be used, for example, with medical machines as fMRI) or EyeTech, that has multiple external trackers; some of them, like **VT3 XL** (EyeTech, 2020) (N/A), are even made for long-distance eye-tracking (up to 3 meters). Mirametrix's **S2 Eye tracker** (2011) (Mirametrix, 2020) has a face, eye and gaze tracking modules made to provide controller input (instead of mouse or keyboard); the company is currently working on the integration of the tracker into Lenovo (Lenovo, 2020a) laptops.

6.1.2 Glasses

The second category of eye-tracking systems is made by devices that resemble glasses, but they have built-in cameras that do the tracking. The glasses are often easy to wear, and the user can move freely while still being able for the eye-tracking system to work. There are usually at least two cameras – one, a scene camera, that records whatever the user sees, and then a camera that records the user's eyes. However, the device itself can often block the users view in some way.

The other drawback of eye-tracking glasses (as well as of HMD integrated eye-tracking) is that every (even slight) shift of the device on the user's head (for example, because of gravity or rapid head movements) can make the tracking imprecise because the current settings will become invalid.

Tobii VR (Tobii VR, 2019a) created **Tobii Pro Glasses 2** (2014) (Tobii Pro, 2020b) that by design resemble regular glasses and have up to 100 Hz sampling frequency, a slippage compensation and four cameras for the eye-tracking. It can even compensate dioptric lenses from -5 up to +3 diopters. With a special recording unit, it can even work without connection to the computer for 2 hours. The device also provides a live stream of what the user sees, which can help further analyze his gaze. However, it supports only dark pupil tracking. The device is displayed in figure 33.

Figure 33 Tobii Pro Glasses 2 (Tobii Pro, 2020b)

In 2019, Pupil Labs (Pupil Labs, 2019a) released **Pupil Invisible** (Pupil Labs, 2020), a head-mounted eye-tracking system that looks like normal glasses and can accommodate -8 to +8 diopter lenses, can be controlled from an Android device, and data can be uploaded straight to cloud.

German company SensoMotoric Instruments has created ETG – **Eye Tracking Glasses** (2014) (Wayback machine, 2018) – but Apple Apple, Inc., 2019 later bought the company, and no information about their products are available.

Arrington research also provides a wearable tracker – **SceneCamera** (beginning of the 2010s) (Arrington Research, 2020c) that can be used with both dark and bright pupils, as well as in monocular or binocular version and has slip correction.

Numerous other companies make eye-tracking glasses, such as **SR Research** with their EyeLink II (2001) (SR Research, 2020b), which has a sampling frequency of up to 500 Hz.

6.1.3 HMD Integrated Eye-Tracking

HMDs (head-mounted displays) are one of the most promising fields of technology where eye-tracking can be used. Integrating eye-tracking into HMD is often very easy because the user already has to wear some device, so it does not bring the user any more discomfort. Also, the HMD's eye-tracking can often be used in the virtual environment to help him control the UI or ease the system by foveated rendering.

Pupil Labs (Pupil Labs, 2019a) provides add-ons for several HMDs (HTC Vive (VIVE, 2019) released in 2019, displayed in figure 34, Epson (Epson, 2019) and HoloLens (Microsoft, 2020a), both released in 2017) (Pupil Labs, 2019b). The add-ons are glasses placed under the HMD, which provides precise measurements due to the closeness to the pupil. The drawback is that with HMDs, there is often not enough space between the user's face and the HMD, and an additional layer between them could make the user more uncomfortable. Also, it does not fit well with glasses, and if it does, the reflections make the tracking imprecise (Hume, 2016) even though the creators state otherwise (Kassner et al., 2014) (Researchgate, 2019). A big advantage of Pupil Labs' software is that it is open-source. It is also the only eye-tracking that tolerates other IR devices. However, it does not remember settings from the last time, so you have to recalibrate it every time. (Hume, 2016)

Figure 34 Pupil Labs' eye-tracking add-on for HTC Vive (Pupil Labs, 2019b)

FOVE VR headset (2014) (FOVE, 2019) has its own eye-tracking built-in directly into the HMD. It uses two infrared tracking systems that display a pattern on the user's pupils and sensors then collect the data. It is said to be the first eye-tracking headset. The headset's name comes from foveated rendering, which is presented as one of its core features. BThe headset's name comes from foveated rendering, which is presented as one of its core features. Along with fine control with the eyes, it reduces motion sickness and eye fatigue. (FOVE, Inc., 2015) However, some reviewers said it is uncomfortable to wear. (Pretty Neat VR, 2019)

Tobii's cooperation with HTC on **HTC Vive Pro Eye** (2019) (TobiiVR, 2019c) shows it is possible to integrate Tobii's eye-tracking into HMDs too. Tobii also solves the problem of the shifted tracker by creating 3D model of the user's eyes and changes tracking accordingly – it is the only HMD-integrated device that can do that.

LooxidVR (2018) (LooxidLabs, 2020) is a mobile-powered VR headset (the virtual environment is provided by a smartphone put inside the headset), which also has EEG (electroencephalography) built-in the headset, which provides information about the user's brainwaves. This makes it a cheap and easy-to-use device for (not only) medical purposes. However, the fact that it is mobile-powered makes the quality of the virtual environment lower than with HMDs.

Varjo's **20/20 Eye Tracker**, which is used in their VR headset (e. g., new Varjo VR-2 Pro (2019) (Varjo, 2019b)), uses a special custom-made, complex IR illumination pattern (in contrast to the regular dotted pattern). The company claims that it makes it "The most accurate eye tracking ever integrated into a VR device". (Varjo, 2019a)

VRgineers **XTAL** (2018) (VRgineers, 2019), an enterprise VR headset, has a function called AutoEye. Thanks to their integrated eye-tracking systems, users can use AutoEye to automatically measure their interpupillary distance and position the lenses according to user's needs. Visualization of such calibration can be seen in figure 35. In 2020, VRgineers eye-tracking was provided for beta users.

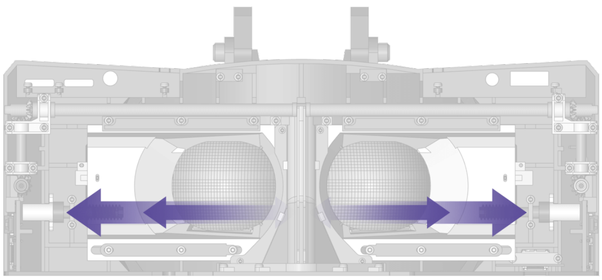

Figure 35 VRgineers' AutoEye system for XTAL (VRgineers, 2019)

Arrington research also provides devices that are integrable into HMDs (Arrington Research, 2020b). Microsoft's **HoloLens 2** (Microsoft, 2020a) supports eye-tracking thanks to two integrated IR cameras that support user authentication based on the user's iris; no other eye-tracking functions are present.

While other devices focus on the line of eye-sight, **Eyefluence** (2013) (Eyefluence, Inc., 2016) focuses on eye-gesture cues and its usability for navigating menus and making selection, basically using it instead of a mouse. They do not use winking, blinking or staring as a means of input, but they process biomechanics of the eye (e.g., the processing of lighting, how the eye reacts to different stimuli) to detect what the user wants to do. They call it "the eye-brain connection". (Techcrunch, 2016) It also has built-in eye detection, so it can scan the user's eyes to authenticate him, so he can access, for example, private information. It also uses a built-in forward camera to scan the environment and, for example, take a picture of what is in front of the user, and then it can process the photo (e.g., upload it online). However, the company was acquired by Google in 2016 (Crunchbase, 2016), and since then, no new information has been released.

6.2 Other Approaches

IR cameras described above are not the only way how to track users eyes. Other solutions can be either very simple devices that use web cameras or more biological approaches, like electro-oculography or scleral search coil that both use internal processes of the user's head to track the eyes.

These approaches are rarely used in larger scope because of either their low precision or their invasive nature. None of them is used in virtual reality, but they should be stated here for the sake of completeness of the summary.

6.2.1 Web Camera Eye-Tracking

Webcam eye-tracking is the cheapest and most accessible because web cameras are easy to get and are often integrated into laptops or tablets. All you need is eye-tracking software, which uses the images from the web camera to recreate the user's eye only from the visible light spectrum. However, the drawback is that this approach is not very accurate because of the short visible spectrum and the needed balance between high resolution and latency – high-resolution cameras create a better image of the eye, but their processing speed (and the speed of the software) is slower, which increases the latency of the tracking. The third drawback is the ambient light condition because low lighting causes less contrast between the eye and the face, making it hard to detect only the eye. (Jensen, 2020)

XLabs Gaze is a free plugin for the Google Chrome internet browser (Google, 2019) that allows users to track their gaze on any device that runs Google Chrome. The user can calibrate it manually and then start dynamic calibration, which improves the tracker precision over time. Users can then use their gaze to scroll the web, open links or just track and record their gaze. The drawback is that the tracker is very sensitive to light conditions and does not work in the dark very well. (Hume, 2016) Also, because it is only a Google Chrome plugin, it cannot be used in external applications.

6.2.2 Electro-Oculography

An approach based on electro-oculography (EOG) was presented by Kaufman et al. (Kaufman et al., 1993) EOG uses electrical impulses sent by the human brain when the eyes move. With two electrodes placed on the skin near the eyes, they can detect electrical changes in the electromagnetic field in front of the human head. That way they, can compute the line of the user's sight and triangulate the position of the object that the user is looking at. This was proved to be not as accurate as other approaches (Heide et al., 1999), but the goal was the inexpensiveness due to the target domain in medicine (e.g., for quadriplegics).

6.2.3 Scleral Search Coil

The scleral search coil method uses a small copper coil embedded in contact lenses placed directly on the user's eyes. The user is placed in AC magnetic field and according to the voltage amplitude in the coil, researchers can measure the eye position. This method is much more precise than EOG because it is not interfered with by other inputs (EOG often detects other electrical stimuli). However, this approach is highly invasive, and users' eyes get sore very soon (30 minutes on average), so it is not made for longer usage (thus, it is not ideal for VR environments) (van der Geest & Frens, 2002). Example of this approach can be seen in figure 36.

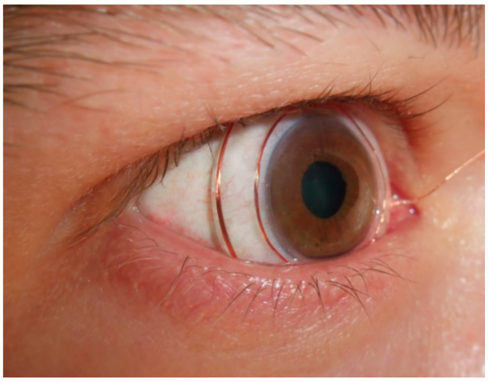

Figure 36 Scleral search coil (vision, 2020)

6.3 Summary

The following table is a summary of the eye-tracking systems. From every company only, one (the best) eye-tracking system from each type is stated. Also, only eye-tracking systems based on infrared sensors are stated because they are the only ones used in VR.

Table 4: Summary of eye-tracking systems

Device	**Freq**	**Lat.**	**Accuracy**	**Tech.**	**# cam**	**Cal.**	**Op. dist.**	**Weight**	**Status**
Tobii Pro Fusion	120	3	0.4°	DP+BP	2	B	50–80	168	CU
The Eye Tribe	60	20	0.5–1°	DP	2	B	45–75	70	NFS
SMI RED500	500	N/A	0.4°	DP	N/A	B	50–80	N/A	NFS
400 Hz Binocular USB	400	N/A	0.25–1.0°	DP	1/2	M/B	20–140	N/A	CU
EyeTech VT3 XL	60	N/A	0.35°	DP	N/A	N/A	120–300	1800	CU
Mirametrix S2	60	N/A	0.5–1.0°	BP	N/A	B	N/A	300	CU
Tobii Pro Glasses 2	100	N/A	0.6°	DP	4	M/B	N/A	45	CU
Pupil Invisible	200	N/A	N/A	N/A	2	B	N/A	N/A	CU
SMI ETG	120	N/A	0.5°	DP	2	B	N/A	47	NFS
Scene Camera	60	N/A	0.25–1.0°	DP	1/2	M/B	N/A	35	CU
EyeLink II	500	7	0.5°	N/A	2	B	40–140	N/A	CU
Pupil Labs	200	9.7	0.6°	N/A	2	B	N/A	N/A	CU

Table 4: Summary of eye-tracking systems

Device	**Freq**	**Lat.**	**Accuracy**	**Tech.**	**# cam**	**Cal.**	**Op. dist.**	**Weight**	**Status**
FOVE	120	N/A	<1°	N/A	2	B	N/A	N/A	CU
LooxidVR	120	4	N/A	N/A	2	B	N/A	N/A	CU
Tobii VIVE Pro Eye	120	10	0.5–1.1°	DP	2	B	N/A	N/A	CU
20/20 Eye Tracker	100	N/A	0.7–1°	DP	2	B	N/A	N/A	CU
XTAL	210	8	N/A	DP	2	B	N/A	N/A	CU
Arrington research	60	10	0.25–1.0°	BP/DP	2	M/B	N/A	N/A	CU
Microsoft Hololens	N/A	N/A	N/A	N/A	2	B	N/A	N/A	CU
Eyefluence	N/A	N/A	N/A	N/A	N/A	N/ A	N/A	N/A	NFS

Freq. – reported data frequency in hertz

Lat. – latency of the system (lag) in milliseconds

Accuracy – accuracy in degrees (the difference between real and computed eyesight line)

Tech. – used tracking technology (DP – dark pupil, BP – bright pupil)

 # cam – number of front cameras (that are tracking the eyes)

Cal. – calibration type (M – monocular, B – binocular)

Op. dist. – operational distance (how far from the user the tracking should be), in centimeters

Weight – the weight of the tracking system in grams

Status – the status of the tracking (PR – prototype, CU – commercially used, NFS – not for sale)

N/A – information could not be found

6.4 Discussion

Eye-tracking goes through a rise these days. Apart from its undisputed advantages in usability testing, more and more virtual reality devices will include this technology to provide better and faster results for their users. Foveated rendering, improved interaction techniques and realistic avatars will be used more and more with the gaming industry and cooperations slowly and steadily moving to the virtual space.

Add-on optical tracking can even be used as dioptrical glasses, where every user will have his own eye-tracking add-on, each with different lenses.

On the other hand, desktop-mounted devices are more of a temporary phase that will decline in the following years. More precisely, it will leave the desktops of regular users and use its potential in medicine to work with patients who can only communicate with their eyes.

Eye-tracking in glasses will also be more and more frequent as augmented reality training and games will find their way into our lives and homes. Their simplicity enables them to work in combination with dioptrical glasses, so we can benefit from both without changing our appearance by wearing some complicated device.

Intrusive eye-tracking, which requires the user to put something in his eye, is currently too uncomfortable for the user. This approach needs to be as easy to use as regular dioptric lenses for it to be utilizable.

7 Locomotion

Moving in virtual reality is one of the key components of the user interface. A lot of VR worlds need to enable the user to change his location to provide a fully immersive experience, but users can suffer from cybersickness (motion sickness in the virtual world) when the movement is not synchronized with the user's real movement. There are a lot of ways how to achieve that, and some of them even do not need any physical controller.

Apart from positional tracking (see section 3), locomotion does not require so much space – it is mostly in a form of a (moving) platform, that allows the user to walk and run on a place – without changing his position. This allows the user to cover more ground without actually needing more space than the locomotion devices takes up.

However, it is at the expense of immersivity, because locomotion devices do not provide the actual sensation of real-life walking. The user often slides, walks in place or runs in a sphere, which can be both unrealistic or tiring. So, in this section, we will mainly focus on the immersivity of the device, its realistic transfer of feet movement, speed limitations and comfort to the user.

The main categories of locomotion devices are two types of treadmills – **linear treadmill** and **omnidirectional treadmill** – non-treadmill devices – **motor-powered devices**, **user-powered devices** – or **walking-in-place**. It is worth to be noted that some treadmills also use positional tracking sensors that track the user. The usage of sensors can be crucial, because, as Haruo Noma states: "..., it is difficult to sense walking speed directly, and a mechanical delay cannot be ignored, so the system has to adjust the belt speed by referencing the user's position and walking speed in some way." (Noma & Miyasato, 2009). Positional tracking sensors are discussed in Section 3.

7.1 Treadmills

Treadmill is a device generally used for walking, running, or climbing while staying in the same place. In terms of locomotion, it can be used to allow the user to walk freely in the virtual environment without the fear of hitting a wall or some object. It can be either **linear treadmill**, which allow only to walk in one direction, or **omnidirectional treadmill**, where the user can also walk to the sides.

7.1.1 Linear Treadmills

Linear treadmills are the most straightforward way to allow the user to move freely, although the movement is possible only in one direction. The direction of the travel can be changed by either a joystick or rotating the whole treadmill (and thus the virtual world); the first option is undoubtedly simpler.

Unfortunately, there are also other limitations. For example, for sidestep and walking uphill/downhill, special construction is needed.

This can be achieved by a tiltable tethered linear treadmill, such as **Sarcos Treadport 2** (2000) (University et al., 2000), where tether force of pull and push can simulate gravity and slope. The tether also measures position and orientation to have active control over the belt speed and orientation. The limitation of this machine is that the tilt mechanism is rather slow, and fast slope transients cannot be realized by tilt. Also, tilting complicates the ground and wall projection of the virtual world.

7.1.2 Omnidirectional Treadmills

Another way how to transfer user's real movement to the virtual environment is to use omnidirectional treadmills. They detect the user's walking motions and negate them in a way that, due to the counter-movement of the device, the user always stays at the same place, no matter the direction or speed of the movement. It can be, for example, a belt-based treadmill or conveyor roller.

CyberWalk (2008) (Guizzo, 2010), by German researchers at Max Planck Institute of Biological Cybernetics, is basically an array of synchronous linear belts that moves in one direction, while each belt can also move in a perpendicular direction, thus creating an infinite plane with 3 DOF. The platform's five-meter size makes it the largest VR platform, thus enabling the user to move more freely than other platforms. The device can be seen in figure 37.

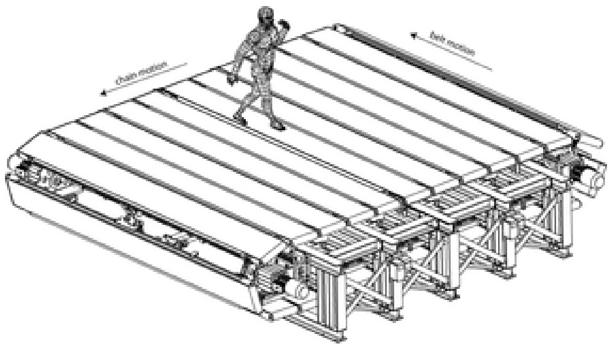

Figure 37 CyberWalk omnidirectional treadmill (Guizzo, 2010)

Torus Treadmill (1999) (Iwata, 1999) from the University of Tsukuba, Japan, works on the same principle as CyberWalk, creating an infinite plane from ten rotating belt conveyors. The plane is rather small, only one square meter and the maximum speed is 1.2 m/s (due to the rotation speed of the treadmills). The position of the walker is fixed in the real world by a computer-controlled motion of the conveyors.

Omnifinity's **Omnideck** (2011) (Omnifinity, 2019) is not based on conveyors, but rather on a motorized treadmill that uses 16 wedge-shaped modules to create a 360-degree walking area. The wedges are made of spinning tubes that are put in motion by the motor. That effectively counters the user's movement, moving him into the centre of the walking area (which is static), so when the user stops walking, he is brought back to the centre slowly. The speed of the rollers is controlled according to the positional tracking data.

Infinadeck's (2014) (Infinadeck, 2019) first publicly presented version (third version of the device overall) was a simple omnidirectional treadmill made of smaller treadmills, and the user was supported by a mechanical arm hanging from a supporting structure. A sensor that tracks users movements is built in the supporting structure, so no additional sensors are needed. (VRvibe, 2016) Second public version (fourth version overall, displayed in figure 38) that will be the first commercially distributed is a smaller, more compact solution based on a supporting ring. It provides a 360-degree moving floor that allows for true and natural movement. An active wireless control system in the treadmill instantly reacts to the user's movements without any harness or special shoes required by the user. Outline of the ring can also be displayed in the virtual world for the user to see the constraint. The treadmill always tries to centre the user on the platform. The disadvantage of this is that when the user walks forward and then stops, the treadmill will still try to negate his movement, and the user ends behind the centre. The platform then has to centre him again, which means to move his body even though the user does not move by himself. (Smarter Every Day, 2018) (Infinadeck, 2018)

Figure 38 Infinadeck version 4 (Infinadeck, 2019)

7.2 Non-Treadmill Devices

Even though treadmill devices remind real-life walking the most, devices that do not resemble treadmills are also common. They can be split into two categories – **Motor-powered devices**, where the movement of the devices is provided by some acutator, or **user-powered devices**, where the user uses his own motion to control the device.

7.2.1 Motor-Powered Devices

Researchers from the University of Tsukuba, Japan, came up with Gait Master. **Gait Master 1** (1999) (VR Lab, University of Tsukuba, 2019b) is an omnidirectional interface that simulates uneven surfaces, thus supports not only horizontal movement, but also vertical. It is made by two 3 DOF bases mounted on a turntable. A walker stands on top of the plate on the motion-base. Each motion-base is controlled to trace positions of the feet, and the turntable traces the orientation of the walker. The working area of the footpad is rather small, 32 cm back-and-forth, 28 cm left-and-right, with 20 cm up-and-down. Also, the maximum speed is only 50 cm/s. (roidroid, 2011)

Another version of this device is **GaitMaster 2** (2000) (VR Lab, University of Tsukuba, 2019b), which can be seen on figure 39. This second generation of Gait Master is not omnidirectional, but linear, and has only 2 DOF (one for each foot). The platform tracks the user's feet, and it carries them back to a neutral position (where both feet are on the same level), thus negating the user's movement. Thanks to that, the user maintains his position all the time, even as he moves up and down a virtual staircase.

Figure 39 GaitMaster 2 (VR Lab, University of Tsukuba, 2019b)

CirculaFloor (2002) (VR Lab, University of Tsukuba, 2019a) by the researchers from the University of Tsukuba, Japan is a system of omnidirectionally moveable floor tiles that read the user's next step with a sensor and move there accordingly, thus creating an unlimited plane. The tiles can move while the user is standing on them, so they can operate in a limited space (the position of the walker is fixed in the real world). It is made possible with a holonomic drive built-in each tile and software that computes re-centring of tiles based on motion cueing. The system can also provide vertical movement because the tiles can change their height to some extent. The other advantage is the compactness of the system. The main drawback is safety due to susceptibility to mechanical/software failures because any error can lead to the wrong positioning of a tile, thus the user's fall. Also, the system is slow, and the walking feels unnatural. This device can be seen in figure 40.

Figure 40 CirculaFloor prototype (VR Lab, University of Tsukuba, 2019a)

In 2007, the researchers from the University of Tsukuba also presented **String Walker** (VR Lab, University of Tsukuba, 2020). This time, the user's shoes were connected to four strings each, and the strings were connected to motor pulleys on a turntable. The strings pulled the shoe in the opposite direction of walking, so the step was cancelled. This way, the user could walk in all directions (even to the side or walk backwards). The pull of the strings is applied after the swing phase of the shoe movement, so when the user places his left foot forward and lifts the right foot, the left foot is dragged to the centre of the platform. The maximum tension of each string is 25 newtons.

The researchers at Max Planck Institute of Biological Cybernetics created **CyberCarpet** (2008) (Luca et al., 2013). It was a prototype of a device based on a ball-array board, which negated the user's movement, thus allowing him to move indefinitely in any planar direction. The platform controller will counteract the user's motion by pulling him toward the centre of the platform.

7.3 User-Powered Devices

User-powered devices have no external actuation and can be, for example, weight or force driven (e. g., low friction surfaces, which negate the user's movements by allowing him to "slide" on the spot). All the movement is created by the user only.

The most recognizable user-powered omnidirectional devices are so-called "hamster balls" – hollow spheres placed on a special platform that allows the sphere to rotate freely, according to the user's steps.

The sphere's rotation is then processed in real-time and transferred to the virtual environment, moving the avatar accordingly. The main disadvantage of this technique is the momentum – once the sphere gains some speed, it tends to keep it and rotates even though the user already stopped walking. The second disadvantage is that the way you walk in real life is not possible in a giant sphere – users still have to do baby steps due to the curvature of the surface, the floor of the ball feels uneven, and the steps feel unnatural for the user.

One example of this kind of device is **Cybersphere** (2003) (Fernandes et al., 2003), which consists of two spheres – one big sphere (called the primary projection sphere), with 3.5 meters in diameter, supported by means of a low-pressure cushion of air, where the user can walk freely. This sphere's movement is transferred to another, smaller sphere (called the secondary rotation sensing sphere), located underneath it. The smaller sphere is tracked by sensors, which then translate the movement to the virtual environment. The primary projection sphere also serves as the main display device because the virtual environment is projected onto the primary projection sphere from the outside, making it visible for the user due to the transparency of the material the primary projection sphere is made from. The virtual environment is projected onto the primary projection sphere by five projectors (four on the sides and one above the sphere), which creates a truly immersive environment.

Another omnidirectional device is **Virtusphere** (2005) (Virtusphere, 2019). In contrast to Cybersphere, it is much simpler both in motion and virtual environment projection. Virtusphere consists of only one sphere with 2.5 meters in diameter placed on a wheeled platform (see figure 41). That allows the sphere to move freely in all directions. For the user to help to maintain his stability and sense of perspective, inside the ball can be a ring around his body that he can hold on to. Three legs on wheels support the ring, so it moves with the user (Markiplier, 2014). The virtual environment is shown to the user via HMD, so the feeling of immersivity is not so strong as with Cybersphere. The tracking of the user is made by Polhemus G4 (Polhemus, 2019) tracking system (see 3.2.2). It offers 6 DOF on its own, without any additional sensors in the sphere itself.

Another possibility for a user-powered locomotion device is the usage of some gait negation technique. Gait negation techniques are based on low friction surfaces, where the user walks on slippery ground. This approach is affordable, and it provides omnidirectional movement. On the other hand, it has several drawbacks. It requires specialized (slippery) shoes/socks, and walking does not feel very natural

Figure 41 Virtusphere (without the supporting ring) (Virtusphere, 2019)

(it is more similar to skating on ice). Also, the learning curve is not as straightforward as with other techniques because the users have to trust both the device and themselves, because at first, they can have a feeling that they are falling. Also, the user has to be held by a special kind of mechanical construction to enable more stable movement.

One of the first prototypes using this technique was **Virtual Perambulator** (1995) (Iwata & Fujii, 1996), created at the Institute of Engineering Mechanics, University of Tsukuba. The first prototype used a harness and roller skate, as displayed in figure 42. The users would hang from a supporting arm, strapped in a harness and would wear a roller skate to enable the user to move. However, the users felt uncomfortable because of the pressure of the parachute-like harness, so the prototype was improved by replacing the harness with a belt around the waist. A rubber toe was added to the roller skates to allow the user to break. After that, the roller skates were replaced with a low friction pad and socks with a rubber toe, on which system a lot of user-powered omnidirectional devices are now based.

Cyberith Virtualizer (Cyberith, 2019) (both R&D kit and Elite version, the second generation of the device, released in 2019, can be seen in figure 43) is one of the devices based on the technology of the Virtual Perambulator. However, the user is supported by a ring held by three mechanical arms. The user is strapped to the ring, which then moves with him up and down to provide the best support. It can be used to scale the avatar in the virtual environment or to detect vertical movement. Six motion sensors in the platform detect user's walking direction and speed. The sensor in the ring detects the user's rotation, so,

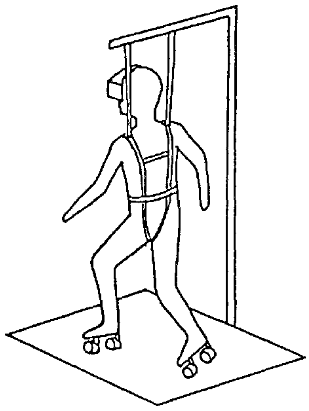

Figure 42 First prototype of Virtual Perambulator (Iwata & Fujii, 1996)

with internal HMD tracking, it allows the user to walk in one direction and look in another. The platform itself also has an integrated vibration unit, which provides additional haptic feedback, thus increasing the feeling of immersion. Any HMD can be used with Cyberith Virtualizer because it is a standalone device. However, the device also has a cable guiding system, which prevents the HMD cable from getting in the user's way. Instead of an HMD, a CAVE system can also be used to display the virtual environment.

Figure 43 Cyberith Virtualizer Elite (Cyberith, 2019)

Wizdish's **ROVR** (2015) (ROVR, 2019) is also based on the low friction surface, but contrary to other devices, it supports not only walking, but also other feet movements, so users can, for example, slide. This can be used for applications like skiing or rollerblading.

KAT Walk (KAT VR, 2019b) and its three versions – **KAT Walk** (2016), **KAT Walk Mini** (2018) and **KAT Walk Premium** (2017), displayed in figure 44 – has a different type of user's body support. It has a special construction, where instead of the user being held by a ring supported by several legs, he is held by a mechanical arm with a harness, which can support the user's weight. Because the user is not hanging from the harness, rather is only supported by it, there is not that much pressure from the harness for the user to feel uncomfortable. It allows users to walk, run, walk backwards, jump, crouch and sit in the virtual world. The movement is not based on a low friction pad because the users can feel unstable, but it uses high friction material surface with constant rolling friction to simulate real walking.

Figure 44 KAT Walk Premium (KAT VR, 2019b)

7.4 Walking-in-Place

Walking-in-place (WIP) is a locomotion technique that is probably the closest to real-life walking. It usually consists of sensors attached directly to the user's feet (or at least ankles) that track the movements of the legs. Users can basically walk in a place, and it is translated into a movement in the virtual environment.

In 2019, KAR VR presented their new product, **KAT Loco** (KAT VR, 2019a). Instead of the gait negation technique, this time, they use wireless sensors placed directly on the user (ankles and waist), which track his leg and body movements and transfer them into the virtual environment. To move forward, the user shuffles around; to move backwards, the user puts one of his feet back; for movement to the sides, the user puts a foot to the side accordingly. To turn, the user turns when shuffling around. To cover longer distances, user can stretch his leg in front of him and lift the toes – the system takes this as a command to move fast forward without shuffling around. This way, the users can move freely without any special platform or without being tangled in wires. Creators also promise less cybersickness, instant movement and analogue speed, with low motion latency to 20 ms. The batteries powering the device are said to run for up to 10 hours. The visualization of this device can be seen in figure 45.

Figure 45 KAT Loco walking in place (KAT VR, 2019a)

Stompz (in development since 2009) (Stompz, 2020) is a WIP device with two controllers placed on the top of the user's feet that track their movement. The controllers are tracked by a USB receiver connected to the computer, laptop or tablet. The receiver can be either placed on the HMD or at a distance of 10 meters. It supports a multi-user experience, both local or with users across the globe.

Another walking-in-place locomotion controller is called **Cybershoes** (2018) (Cybershoes, 2019), which uses special shoes with a built-in IMU unit, roller for accurate tracking and grips on the front of the shoes for better traction. User takes on Cybershoes over his shoes and sits on a turning chair, under which is a special antistatic carpet provided by the Cybershoes company. The user then "runs" while sitting, so the movement is far from natural. Two different settings are possible – either the virtual avatar moves the same way as the user runs or in the way where the user stares. The shoes work wirelessly via radio frequency; however, the transmitter connected to the PC must be nearby. The internal shoe battery lasts up to 10 hours.

Several methods for walking-in-place that used only position and orientation tracking integrated into HMDs were proposed, with various precision, the ones using PC-based HMDs (J. Lee et al., 2018) proving better than smartphone-based (Tregillus & Folmer, 2016).

7.5 Other

Even though walking (or at least some approximation of it) is the most widely used means of locomotion input, a few others that are worth mentioning. Note that many others exist (for example, based on steering), but the following are examples of other locomotion devices that have at least some closeness to virtual reality locomotion.

7.5.1 Cycling

If walking is not needed, but there still is a need to move the avatar in the virtual world, cycling can be used. It is a movement that users are often used to and can be very easily provided for the user, either with a real bicycle on a special platform (as did researchers from Graphics, Visualization, and Usability Center from Georgia Tech University) (1998) (Georgia Tech, 2020), unicycle on a turntable called **Sarcos Uniport** (1999) (Sherman & Craig, 2002), simple exercise bike (**VRBike** by researchers from Max Planck Institute (end of the 1980s) (Max Planck Institute, 2020)) or customer-available exercise bike **VirZoom** (2016) (VirZoom, 2020).

7.5.2 Rudders

Rudder VR controllers are based on a platform, where the user puts his feet and controls the locomotion of the virtual avatar by tilting the platform, just like a joystick. It is a very simple device that requires limited space, but it also has limited possibilities in terms of types of movements, and it can cause fatigue by unnatural movements of the user's legs. Also, cybersickness can be present because there is no correlation between the avatar movement and the user's movements (because there are not any).

3dRudder (2019) (3dRudder, 2019) is an example of such a device. It provides 6 DOF – you can move forward-backwards and to the sides simply by tilting, pitching and yawing, but thanks to its touch-sensitive deck the user can also control vertical movements by lifting his foot. Every application can set what concrete movements do. By the angle of the tilt/pitch, users can change the speed of the movement. No haptic feedback in the unit is currently present. (Shugghead Gaming, 2019) The device can be seen in figure 46.

Figure 46 3dRudder (3dRudder, 2019)

HoboLoco (2018) (HoboLoco, 2020) is based on gyro board technology – a self-balancing board, where the footpads also serve as pedals. It provides haptic feedback for the user to really feel immersive.

Another device is **Joyman** (2011) (Marchal et al., 2011), which is basically a human-scale joystick for navigating in virtual worlds. The user leans towards/pulls a stick connected to the centre of the device platform, and the virtual avatar moves accordingly.

VRGO Mini (2020) (VRGO, 2020), the second main product from VRGO company, is a gyro board seat placed on any chair, and the user controls the movement by leaning and tilting his whole body.

7.6 Summary

The following table is a summary of the locomotion systems. From every product, only the newest version is stated. Also, only devices based on walking are stated.

Table 5: Summary of VR locomotion systems

Device	DOF	Maximum velocity	Working area	Status
Sarcos Treadport 2	6	19	6 x 10 x 0	PR
CyberWalk	3	2	5 x 5 x 0	PR

Table 5: Summary of VR locomotion systems

Device	DOF	Maximum velocity	Working area	Status
Torus Treadmill	3	2	1 x 1 x 0	PR
Omnideck	3	UL	4.2 x 0	CU
Infinadeck	3	6	1.3 x 1.7 x 0	CU
GaitMaster 2	2	1.5	0 x 80 x 20	PR
CirculaFloor	3	0.3	UL	PR
String Walker	3	N/A	1.8 x 0	PR
CyberCarpet	3	2	0.8 x 0	PR
Cybersphere	3	UL	3.5 x 0	PR
Virtusphere	3	N/A	2.5 x 0	CU
Virtual Perambulator	3	UL	N/A	PR
Cyberith Virtualizer	3	UL	1 x 0	CU
ROVR	3	N/A	1 x 1 x 0	CU
KAT Walk Premium	3	UL	1 x 0	CU
Vue VR	3	UL	1.2 x 0	CU

DOF – number of degrees of freedom

Maximum velocity – the maximum possible velocity in meters per second (UL – unlimited)

Working area – the working area of the tracking (width x depth x height or diameter x height), in meters

Status – the status of the tracking (PR – prototype, CU – commercially used)

N/A – information could not be found

7.7 Discussion

Locomotion controllers provide a small and compact way to move in the virtual world. That makes them very handy for gamers or people with limited available space in general. Still, they are not very suitable for industry or big gaming events, which often have large halls for users to roam.

These devices often limit the user in speed and freedom of movement because the fast changes in direction can result in the user losing his balance and falling. They are also often unnatural to use because the user slides instead of walking.

The two most promising approaches are active omnidirectional treadmills and walking-in-place. Omnidirectional treadmills provide the closest thing to walking and real life. When technical difficulties like speed limit or incorrect centring are overcome, it could be a very handy tool for moving in virtual worlds. If the treadmill could also provide movement in up and down direction, for example, by elevating/lowering parts of the treadmill, it could increase the user's experience even further.

Walking-in-place with sensors strapped to the user's body is an easy and natural way of locomotion, even though it can be tiring for the user. If a full-body tracking suit would detect walking-in-place without the need for any additional sensor, it would once again bring us closer to an all-in-one solution for interaction in VR.

For specialized applications requiring the user to ride a bicycle or fly, there will always have to be some devices that aim directly on that use case to be natural.

8 Conclusion

This work gave an overview of various devices for interaction with virtual worlds in virtual and augmented reality. These controllers were separated into several categories according to their primary means of input, and their advantages and disadvantages were presented.

Positional tracking systems determine the user's position in the tracked space, allowing to move the virtual avatar in the virtual world accordingly. Hand-based controllers utilize our hands as the primary means of input to allow users to interact with virtual objects by simply moving their hands and fingers. They are split into a myriad of categories according to the usage of external devices. Body tracking and wearable body haptics provide additional positional info about the user's whereabouts and movement of their torso and limbs. They can also be used to provide haptic feedback. Eye-tracking systems use eye movements to help the user orient in the virtual world and coordinate limbs and the rest of the body. Locomotion systems can serve as an addition or a replacement of positional tracking systems for helping the user to travel in the virtual world. By combining more of these controllers, the user's feeling about the immersiveness of the experience can be increased.

New controllers are created every day, not only by researchers in VR laboratories but also by companies that focus on gaming or business. Virtual reality is on the rise and evolving with great speed, and there is no telling which approach will prevail. However, we can be sure that virtual reality will change our world and how we work in many ways.

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