Hand-held Haptic Feedback for Virtual Reality

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Figure 1: a selection of hand held haptic feedback devices, on the left the Transcalibur [12] a device for 2d shape rendering, in the middle is the Haptic Revolver [21] which is able to render surfaces and on the rightis the Drag:on [24] which is able to simulate different aspects of an virtual object using drag force

ABSTRACT

Haptic feedback is an essential part of making virtual reality experiences more immersive. It includes force and tactile feedback which is provided to the user through a haptic interface. As the hands and arms of users are in most cases the body parts with which the interaction with the virtual world occurs, it is crucial to give the user haptic feedback on those. In this paper we will focus on the current state of research in this field and will discuss work on this subject within the last three years concerning the question how haptic feedback can be conveyed to the users' hand, wrist, or lower arm. It showed that there is a lot of development going on in this field and that there is a huge potential for improving VR experiences with haptic feedback devices.

CCS CONCEPTS

• **Human-centered computing** → **Virtual reality**; **Haptic devices**.

KEYWORDS

hand-held, haptic feedback, vr, virtual reality, feedback

1 INTRODUCTION

Haptic feedback has been around for several years now and is since the beginning of research in Virtual Reality, a big part of making the Virtual Reality experience immersive. In the past, we were not capable of creating sufficient enough hardware and software solutions due to limitations in technology. But meanwhile powerful hardware, which provides enough computing power for virtual reality, is widely spread among researchers and even end-users to support new technologies for representing haptic feedback. Researchers have developed many prototypes for haptic feedback over the last years, and there are even commercially produced devices that provide various degrees of haptic feedback today. As Je et al. [8] stated "consumers pushed forward to untethered VR, researchers turned away from solutions based on bulky hardware and started exploring smaller portable or wearable devices".

More and more manufacturers started to develop and produce virtual reality hardware as the production costs got lower and the general public got more interested in the topic. Over the last 3 years, we saw significant growth in sales of virtual reality headsets as seen in Figure 2 and the segment has further been forecasted to grow and hit shipments of around 76 million units by 2024 [18]. As the role of virtual reality gets more significant in many sectors of human life and is used by more and more people there is a need to shrink down the devices which are needed to provide a sufficient VR experience. With this aspect in mind, it is only logical that there will be an increased demand for hand-held, wearable, or similar devices that can convey haptic feedback to the user's hand, wrist, or lower arm.

In this paper, we will focus on what is currently research but may well be available to the general public in just a few short years. Therefor a systematic literature review (SLR) was conducted. Many researchers and developers are currently working on novelty hard and software solutions to fulfill the steadily increasing demand for various virtual reality solutions. As it will be shown in the discussion there are many different approaches to how and what kind of haptic feedback can and will be conveyed to the user's hand, wrist, or lower arm. For that, the different approaches and technologies

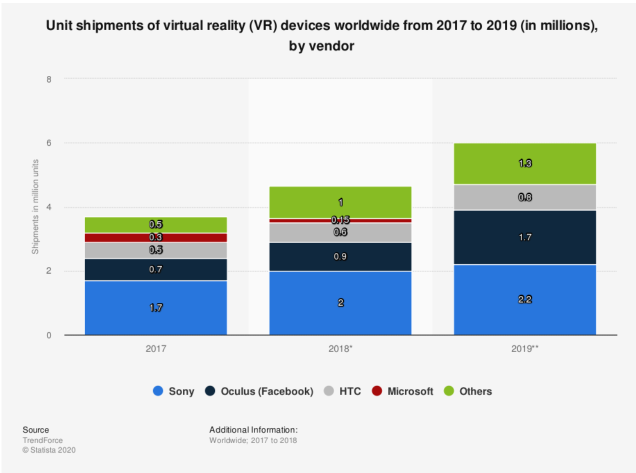

Figure 2: increasing Unit shipments of VR devices worldwide from 2017 to 2019[19]

will be split and sorted into groups to show trends and similarities in current research. From these research devices and technologies many will probably never leave the research state as they are, but may be combined with other solutions to make it to commercial production one day. It's important that researchers lay the foundation with simple devices and solutions today so that we can build on it in the future.

2 METHOD

At first, it was looked at the research question and the keywords were brought down to the relevant ones as follows, "Hand-held", "Haptic", "Feedback", "Virtual Reality" because we are mostly looking for hand-held devices, which give us haptic feedback and all that in the aspect of virtual reality. Then it was briefly looked through the most relevant sites for research in those fields for scientific papers, and the ACM Digital Library was chosen as a starting point for the research. So the research began in November 2020 with the keywords in the abstract and timespan from January 2017 till November 2020 as limiting factors. This approach yielded 35.000 results. The results were then overlooked and further limited down to only show papers from CHI '20, this revealed 446 results. Then these were sorted through by reading the title first, and if it sounded compelling the abstract was read and it was looked at attached videos if available. Then the following inclusion criteria were applied to it:

1. Written in English
2. Published between January 2017 and November 2020
3. An article from a major conference
4. Title or abstract includes at least one of the before mentioned keywords
5. A developed prototype device of some sort

This resulted in a pretty good overview of the papers looked at. If the paper included relevant new information it was added to the set. This process was repeated with CHI '19 (430 results), UIST (330 results), and VRST (352 results) until there were about 25 papers that sounded promising for the research. After that, a second approach was taken for a broader overview and searched with the same timespan and keywords from the beginning but this time only in the title which yielded about 7200 results. They were looked through until there were a total of 27 papers ready for the research.

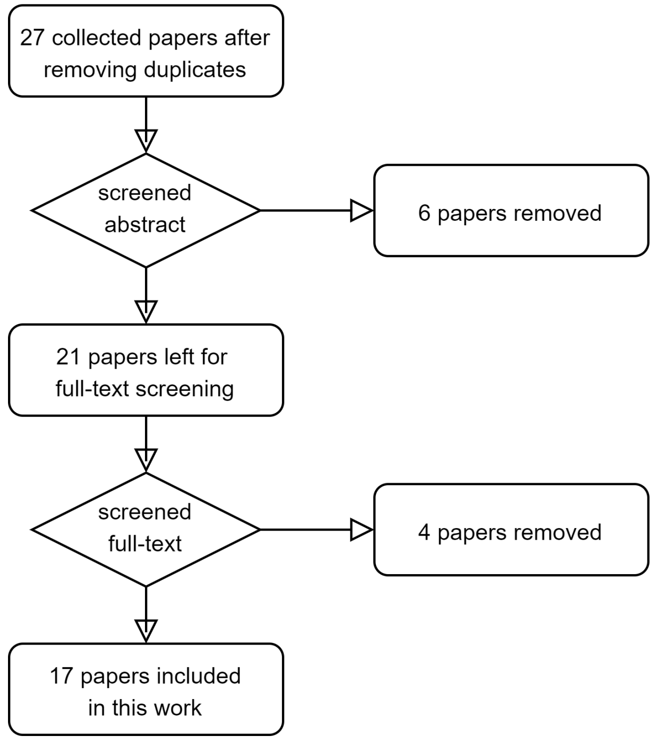

Figure 3: The outsorting process of the collected research papers displayed as flow chart

3 RESULT

With a set of 27 papers reached a closer look was taken at each of the papers screening them, this process can be seen in Figure 3. At first, some work was removed because it didn't exactly fit the research question, furthermore removed was some work that was not in the VR aspect of the research, and work that fitted in the research but only for a very specific use case. Numerous posters were also removed from the set because there already was a sufficient amount of work in that direction in full papers. After that first rough out sorting, the papers were read through and it was decided to remove work that had interesting approaches to haptic feedback but not in the aspect of virtual reality. Also, removed was work that focused more on the controller part of the device instead of the haptic feedback, and works that developed actuators that could be implemented in haptic feedback devices. Through this process, 10 papers were removed which left 17 papers for the research.

4 DISCUSSION

There are many different approaches to provide haptic feedback to a user's hand, wrist, or lower arm, but what they all have in common is to provide haptic feedback to improve the VR experience. We can classify the work in this field by many aspects but in this discussion, we will lay the main focus on two simple criteria, which are the form factor of the device and the nature of the haptic feedback.

4.1 What haptic feedback can represent

There are different types of what can be represented with haptic feedback. We can represent the surroundings of the user with ambient-based haptic feedback for example the temperature or smell of the situation the user is in the virtual world like in the work of Harley et al.[6] where the sensation of being on the beach is created by heat and the smell of sunscreen. Or we can just represent the nature of an object that the user is actively interacting with as object-based haptic feedback which is the main focus of this work. Ambient-based haptic feedback can be perceived more subtle than object-based haptic feedback, but its none less important for an immersive VR experience. But with the current state of technology and development, the main focus is to give object-based haptic feedback to the user. This goes back to that a lot of research is currently done with training and educational processes in mind where an exact representation of, for example, the machinery or in the case of the work from Smith et al.[14] the human body, you are interacting with, is more important with these novelty technologies than an immersive entertainment purpose. Also, it is currently not possible to achieve a full set of ambient-based haptic feedback with the current technologies for a reasonable cost so therefore the work of Harley et al.[6] focuses on low-cost, non-digital, diegetic interactions to achieve ambient-based haptic feedback.

4.2 Form factor

First of all, We can differentiate the devices in an over category by type of devices and from factor. My research showed that mostly the following types, in the aspect of how haptic feedback can be conveyed to the users' hand, wrist, or lower arm, are currently being developed and researched.

type	amount
hand-held	11
wearable	4
free-moving	2

Table 1: Types of Devices discussed in this paper

4.2.1 Hand-held. Devices that the user has to hold on to the whole time he is using them in the virtual world. The user can't let them go because they rely on staying in his hand the whole time. This device can be of a grounded or non-grounded type. These devices won't allow the user to feel virtual objects with all parts of his body. An example of hand-held devices is the Drag:on [24]. This kind of device is widely spread and supplies the main part of devices which are dealt with in the papers, for the following discussion.

4.2.2 Wearable. Wearable devices that the user doesn't have to hold on to the whole time, but are always in some form connected to the body. They can represent different types of haptic feedback than hand-held devices as the user can let go and grab them on demand. They are also able to give more subtle feedback and don't need to occupy the user's hands all the time, but the feedback, similar to hand-held types, is mostly limited to the areas where the device is in contact with the user's body and is not available everywhere. They come in many different form factors, such as finger-mounted actuators, exoskeletons, glove-like devices [7] such as seen in Figure 4 or hand-worn like the Grabity [5]. In this category, there are also numerous devices but far less than in the hand-held category.

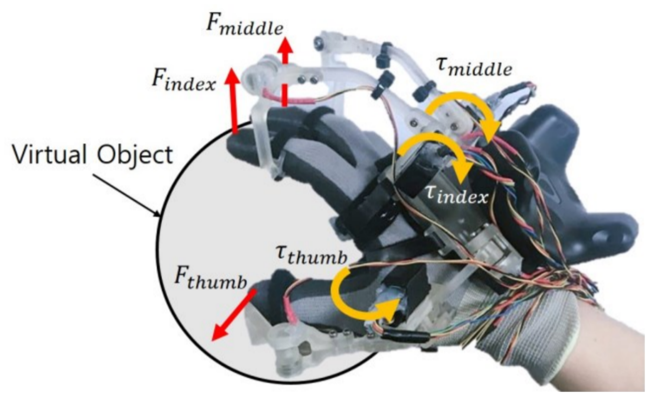

Figure 4: A glove-type wearable device from Son and Park[15]

4.2.3 grounded or non-grounded. Grounded simply means this kind of device is anchored to the ground or your surroundings. So it doesn't rely on the user to hold on to or be worn on the body. While non-grounded means that the devices can be freely moved and is not anchored down somewhere.

4.2.4 encountered-type devices. Encountered type devices are, as stated by Tachi [16], a subset of haptic devices that come in both the grounded and ungrounded format. As a user is not required to wear a device or hold a tool, these devices are enabling the possibility of contact with all body parts on-demand through their multiple degrees of freedom. As stated by Abtahi et al. [2] these devices are most commonly grounded robotic arms that move such that users encounter the end-effector of the robotic arm when they make contact with a virtual object. But they have shortcomings that restrict their usages, such as their high cost and limited workspace. Because of those limitations, researchers have begun the work on hovering encountered-type devices for example the HapticDrone [1] by Abdullah et al. . This type of device marks the smallest part of this discussion with only 2 papers that handle this type of device.

4.3 Types of haptic feedback

There are multiple ways in which haptic feedback can be achieved. Burdea [3] stated that Haptic feedback groups the modalities of force feedback, tactile feedback, and proprioceptive feedback. We will take a look at force and haptic feedback and define some subcategories in which research happened. It's important to notice that devices are in many cases not limited to provide just one or another type of haptic feedback but rather combine multiple types.

4.3.1 Force feedback. Burdea [3] defined that Force feedback integrated in a VR simulation provides data on a virtual object hardness, weight, and inertia. A lot of work focuses on this type of haptic

Figure 5: The Transcalibur device [12] rendering a shape

feedback, but in many different ways. An often seen way is the use of weight and weight shift to simulate different aspects of virtual objects, which include weight but are not limited to. The Aero-plane by Je et al. [8] renders motion paths on a virtual plane with the use of 2 jets, which results in the simulation of weight-shift on a 2D surface. This can be for example used to simulate a ball rolling on a 2D surface or to simulate an egg in a pan in some sort of cooking simulator. Different to this the work of Shigeyama et al. [12] which is about the Transcalibur device which uses changes in its mass properties on a 2D planar area to render a 2D shape, which can simulate the shape of a handheld object as seen in Figure 5. This type of simulation can be used in many different application types as it can simulate a huge variety of 2D shapes, which often occur in virtual reality applications. The SWISH Device by Sagheb et al. [11] in turn aims for a different goal, it uses tracking and motor actuation to actively relocate the center of gravity of a handheld vessel, emulating the moving center of gravity of a handheld vessel that contains fluid as stated in Sagheb et al's. [11] work. As this device again aims for a very specific use-case scenario, in which it provides good haptic feedback it's not usable for a broad variety of virtual reality use-cases. From the category of wearable devices, that use weight or weight shift, we have the work from Choi et al. [5] the Grabity device although it does not put the main focus on weight rendering. It uses two voice coil actuators to create virtual force tangential to each finger pad through asymmetric skin deformation, which produces forces that can be perceived as gravitational and therefore simulate weight. There also is the HapticDrone, an ungrounded encountered type device, from Abdullah et al. [1], which is currently able to provide 1D force feedback through pushing itself in the desired direction when in contact with the user's hand, which when directed to the ground can be perceived as weight. While his approach with quad-copters is limited to a very basic form of haptic feedback the use of quad-copters has big potential as we will discuss later on.

A new approach in haptic feedback takes the ElaStick by Ryu et al. [10] which is capable of simulating the mechanical impedance that a flexible object generates when abruptly swung or shaken by changing the stiffness of four custom elastic tendons along a joint. While this device is only capable of rendering the stiffness of virtual objects it could be interesting in a combination with for example the Transcalibur [12] mentioned above or a similar type of device which can render the shape of a 2D object. An approach at rendering force is provided by ElastiLinks from Wei et al. [20] which uses a pair of controllers that are connected over a rotatable track on each controller to provide a proper point of application of force. The ElasticLinks can simulate the forces generated when pulling a bow or a slingshot. Although this provides good haptic feedback for this specific use cases such as an archery or slingshot simulator type of application, it is not very useful outside of these. Tanaka et al. [17] choose a more established way of generating force feedback with the DualVid device that, instead of using hardware to actually displace the weight like some other research does [11], uses four vibration actuators to generate two types of haptic feedback. It can generate pseudo-force feedback by asymmetric vibrations to render the kinesthetic force arising from the moving mass, and texture feedback through acoustic vibrations that render the object's surface vibrations correlated with mass material properties.[17] Through this mechanism the device can simulate dynamic mass.

4.3.2 Tactile feedback. Tactile feedback is used to give the user a feel of the virtual object surface contact geometry, smoothness, slippage, and temperature [4]. This kind of feedback can be used and generated in many ways, we will look at a few of these and discuss their relevance for virtual reality. A big part in simulating a virtual object is to let the user feel the object in his hand, to achieve that we have to rely on multiple ways of tactile feedback. For an immersive feel, we have to simulate the geometry and form of the virtual object in the hands of the user. To do so many researchers have taken different approaches, Yoshida et al. [23] introduced the PoCoPo, a handheld pin-based shape display that can render various 2.5D shapes in the hand by using 18 motor-driven pins on both sides of a cuboid. But as we can see in Figure 6 this approach has limitations on which size or shape of objects it can render due to its form factor. The work of Sinclair et al. [13] with the CapstanCrunch

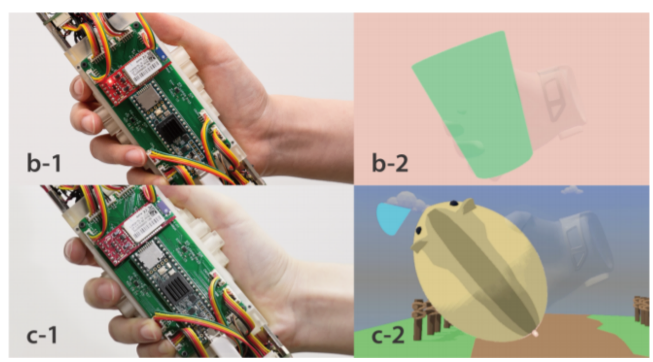

Figure 6: The PoCoPo device [23] rendering shapes of virtual objects

a VR-Controller which also provides grasp feedback to the thumb and index finger uses a friction-based capstan-plus-cord variable-resistance brake mechanism to create human-scale forces without the use of large, high force, electrically power consumptive and expensive actuators. With this technique, the device can simulate for example the push of a button or the use of a scissor, but the high-resolution feedback is limited to the index finger. Therefore if we take a look in the category of wearable devices grasp feedback is also often used to deliver this type of feedback as seen in the work of Hinchet et al. [7] who created the DextrES a flexible and wear-

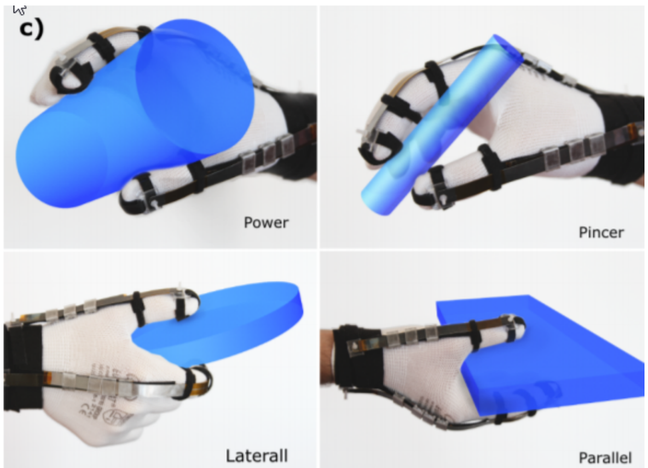

Figure 7: Possible shapes that the DextrES [7] can render

able haptic glove that integrates both kinesthetic and cutaneous feedback using an electrostatic clutch generating holding forces on each finger by modulating the electrostatic attraction between flexible elastic metal strips to generate an electrically-controlled friction force which is used as a braking force to rapidly render on-demand kinesthetic feedback. Also, piezo actuators at the fingertips are used to provide Cutaneous feedback. This approach allows a wide array of possible grasps to be rendered, as seen in Figure 7, and provide haptic feedback for one of the most useful skills we can perform in virtual reality. The work of Son and Park [15] shows how the additional use of haptic feedback to the palm can be used to simulate the size and shape of larger objects in virtual reality and further improve the grasp feedback. Even though this research is on an early stage it further shows the advantages of wearable devices on the hand, as it can render multiple sizes and shapes through only giving the user feedback on the necessary parts of the hand and can quickly adopt to changes in the virtual world as it is not a physical device which the user has to hold in its hand.

As mentioned before there is the Grabity by Choi et al. [5] besides simulating weight it's main focus lays on simulating pad opposition grip forces in virtual reality through rigid grasping force feedback. This feedback is only provided between the thumb and the index finger and is, therefore, less versatile than the feedback created by the DextrES as it is not able to render different shapes. None the less is Grabity an interesting approach through the addition of weight simulation. Another approach to grasp feedback is the Haptic PIVOT, seen in Figure 8, by Kovacs et al. [9] which also doesn't focus on rendering the shape of a grasped object but rather pivots a haptic handle into and out of the user's hand to render the haptic sensations of grasping, catching, or throwing an object on-demand. Although it is not able to render the shape of a virtual

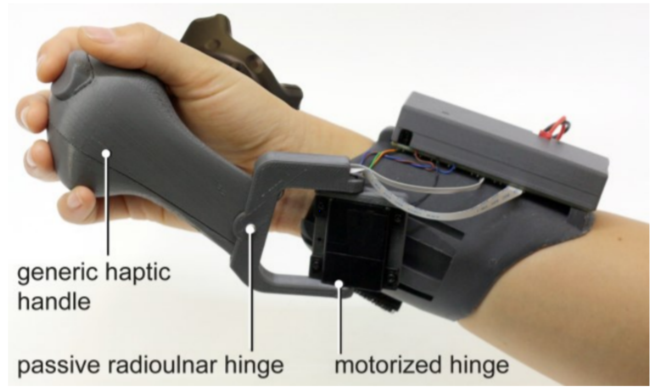

Figure 8: The Haptic pivot device [9]

object, what makes this approach interesting is that it enables rendering forces that act on the held virtual object. Another part of making a virtual object feel realistic even though often unnecessary for many types of applications is the rendering of the surface geometry and texture of a virtual object. The Haptic Revolver an approach by Whitmire et al. [21] can render fingertip haptics such as touch, shear, texture, and shape when interacting with a virtual object using an actuated wheel that raises and lowers underneath the finger to render contact with a virtual surface. The wheel is interchangeable to provide different texture material for different use cases, for example, fur types for a virtual zoo or buttons and switches for a virtual cockpit environment. At last, we have the VR Grabbers by Yang et al. [22], a controller that essentially simulates a pair of virtual chop-sticks. It uses ungrounded haptic retargeting to precisely simulate the grabbing of virtual objects using chops-sticks with a passive controller. This means the controller doesn't actually change anything, once set up, it nevertheless has a realistic feel to the user-generated by tricking him through visual representation in the virtual world. While this again is a very specific use case it may be useful for training purposes, or applications where you need to simulate precise grabbing tools.

4.3.3 Beyond force feedback. If we take a peek beyond the currently typical definitions of force feedback we can look at the work of Abtahi et al. [2] who created HoverHaptics, which uses quadcopters, as ungrounded encountered type devices, to enable rich haptic interactions like dynamic positioning of passive haptics, texture mapping, and animating passive props which can be seen in Figure 9. While this work currently uses passive objects that can be moved around the user's surroundings to match up with objects in the virtual world, this technology has huge potential if combined with traditional haptic feedback technologies such as shape or surface rendering hardware or many others.

4.3.4 The current state-of-the-art and what may come in the future. Now that we have an overview of the current state of research we can take a look at currently commercially available solutions and the technologies used by those. Most, if not all consumer devices that you can buy today use vibrotactile feedback[24], a simple form

Figure 9: Interaction with an passive object attached to the HoverHaptics drone [2]

of haptic feedback through vibration provided by linear actuators or in the most basic form by an electric motor. This allows only for a very basic and abstract form of haptic feedback and comes nowhere near the resolution of the devices mentioned above as they cannot provide different kinesthetic impressions. This form of haptic feedback is widely spread today because it is a well-known method that has been around for many years now and it is also a cheap way to implement some form of haptic feedback into a device. In the future when some of the technologies that are being researched today will prove themself pleasant and reliable maybe this basic form of haptic feedback will become obsolete or will just play a small part in the entirety of a haptic feedback device. But till we reach that point vibrotactile feedback will still be playing a big role in providing, at least some form of haptic feedback today.

Many of the current researched approaches and devices have big potential to provide rich haptic feedback in the future but many of them have limitations. So for specific use cases in which you hold onto a virtual tool, hand-held devices like the Transcalibur [12] or the Drag:on[24] have big potential, but wearable glove-like devices such as the DextrES[7] are way more versatile in terms of grabbing and interacting with many different virtual objects. Maybe a combination of those types of devices could be interesting to see in the future for applications where you need to grab multiple objects but also often need to work with a larger tool that can only be sufficiently simulated by a handheld device. As those devices get smaller and less bulky in the future a combination of them seems pretty promising. Also, a really important part for the future besides using multiple devices combined in applications is the combination of different approaches in a single device so that you have one device capable of presenting multiple forms of haptic feedback and not just lay their main focus one or two kinds like today but rather be able to provide nearly all or even all main types of force feedback and go even beyond that. In my opinion, the future for personal use devices is in wearables because they give the user more freedom to do what they want with their hands and not have to hold on to a device all the time, and could be still portable and relatively cheap to produce. For research and industrial use in a permanently installed environment, I think that the encountered type devices have big potential because they can interact with the user from the outside and could provide more stationary type feedback, for example, walls, that is currently not possible with devices that are hand-held or wearable. But it also makes sense, in this case, to combine multiple types and forms of haptic feedback for example there could be encountered type robotic arms or drones[2] that hand over hand-held devices on a specific location to simulate them hanging on a wall or laying on a table, and all that while the user is wearing some sort of glove-like device which can additionally provide haptic feedback for small objects that the user can grab. All those technologies have big potential to provide realistic haptic feedback and therefore create an immersive VR experience. But a big problem that has to be addressed in the future is still the size and bulkiness of most of the devices that are used to create haptic feedback today. There are promising results like the DextrES[7] Device that have less bulk and is small in size but these are rather the exception.

5 CONCLUSION

A lot of research in this field is currently happening all over the world, as end-users crave for more immersive and sophisticated VR experiences. Most of the devices developed by researchers show that there is a huge potential in hand-held devices that provide haptic feedback to the user, such as the DextrES device [7]. But currently, it is still too expensive to mass-produce these types of devices and there would be currently little to no use for them because developers and manufacturers would have to adapt those technologies into their products. Also, many of the research prototypes that currently exist are, in most cases, only able to deliver a small kind of feedback in a specific direction. As research continues we will be able to combine many of the technologies that are currently being researched into devices that can produce more kinds of haptic feedback. Burdea [4] stated in his work from 1999 that Once the hardware problems are solved, more and more work will be dedicated to making simulations more realistic. We are currently in a period where we have found many solutions to the problems that existed back in the day, but we are not quite there yet to use the full potential that lays in virtual reality. However, if the research continues with the speed and success of the last years there will be more and more capable devices to provide haptic feedback to a user's hand, wrist, or lower arm and make virtual reality experiences even better than they are today.

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