Touching Virtual Reality: a Review of Haptic Gloves

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Abstract

Anyone who has ever experienced a Virtual Reality (VR) environment has dreamed of being able to touch the virtual objects and manipulate them with his or her bare hands. Sadly, that requires much more than just a fast graphic board and an immersive visual display. For multi-finger interaction, this requires some kind of wearable force-feedback device, a so-called 'haptic glove'. The recent growth of the Virtual Reality market resulted in an intensification of development efforts in this technology. These days many teams and start-ups around the world are announcing imminent releases of commercial haptic gloves. Indeed, in the last year there has been one new product announcement almost every month. It is clear that not all new ideas will actually make it to the market, and that not all haptic gloves are addressing the same range of applications. In this paper, the main technical constraints which are faced when designing a haptic glove are addressed with a special focus of the actuation technology. Then, a review of existing devices, past and present projects, comparing their characteristics and performance is provided. Lastly, insights on future developments are sketched.

Keywords: Haptic feedback, Virtual Reality, Haptic gloves, Manual interaction

1. Introduction

Of all VR interaction devices, the haptic glove is at the same time the most desperately asked for and the most complex to develop. Indeed, each human being not only has a unique hand size and shape, but also a pair of hands which are not identical and not even symmetric. In addition, the hand is one of the most sensible parts of the body. It is able to perceive fine details at very large frequencies, but may also develop and perceive large forces [1]. As a consequence, in order to be effective a haptic glove has to be adaptable to its user. It needs to be lightweight and compact, yet deliver large amounts of power with a very low latency.

For many years, the only mature wearable force-feedback devices for the hand have been the CyberGrasp™ of Immersion Corp (now CyberGlove Systems) [2,3] and the Master II of Rutgers University [4]. Neither of them enjoyed a great commercial success. There have been many research projects proposing the use of classical DC motors, artificial muscles, shape memory alloys or dielectric elastomers. An exhaustive review of the developments in academia has been published recently by Pacchierotti *et al.* in 2017 [5]. The purpose of this paper is to focus on commercial devices and to describe the current status of these systems.

2. User requirements and constraints

The sense of touch is extremely complex, and cannot be addressed by a unique actuation principle. For this reason it is common to distinguish between "tactile" and "kinesthetic" touch. Tactile feedback devices provide input to the user's skin. They try to recreate the sensation of a shape, a texture or in some situations even of thermal properties of a virtual object. Kinesthetic feedback devices apply forces to the skeleton of the user. They create an impression of movement and/or resistance through the muscles. In real life, both feedback types are present when touching an object. In order to experience tactile feedback only, one may try to touch an object placed on a slippery surface, so that it offers no resistance. Similarly, one could isolate kinesthetic perception by touching an object while wearing very thick gloves effectively filtering out the tactile component.

The main user requirements for a haptic glove are as follows: the glove should provide both tactile and kinesthetic feedback, it should be wearable (i.e. not heavy) and should not impede the natural movement of the fingers. Because the need to produce in large numbers to reach an acceptable market price, gloves either need to fit an arbitrary size and form of the hand or should be easily adaptable. Latter constraint is usually addressed by offering a selection of sizes within a certain working range. This approach is to some extent similar when purchasing rubber gloves for the household. However, it is not as simple as that as it becomes tedious when actuators need to be placed very precisely relative to the user's anatomy.

3. Classification of haptic gloves

To simplify the analysis, the following classification of haptic gloves is adhered to in this work:

1. traditional gloves,
2. thimbles and
3. exoskeletons.

Although the different classes all share the same objectives and constraints, the three categories follow very different technical approaches to meet with the said objectives and constraints. In the following the three categories are explained and examples of representative commercial products are analyzed in greater detail.

Under the name "traditional glove" a garment made of some sort of flexible fabric, which fits the shape of the hand and lets the fingers move individually, is understood. The sensors to measure the flexion of the fingers and the actuators to apply a feedback on the skin or skeleton are either sewn within the fabric or fixed on the outside of these gloves.

The designers of this type of haptic glove face several challenges. First, the sensors and actuators must be small enough to fit inside the fabric or to allow placement very close to the fingers. Second, the whole equipment (including wiring) needs to be very flexible, otherwise the user will feel restricted in his/her movement. Third and last, the glove must be able to sustain large deformations, including stretching that appears when fitting in and out. The glove should undergo these deformations repeatedly without damage to its structure or affecting its functionality.

3.1. Traditional Gloves

The Spanish company Neurodigital Technologies has announced the development of such a haptic glove, in two versions, the Gloveone™ and the AvatarVR™[6]. Both products provide interaction with the 5 fingers, with 10 vibrotactile actuators placed as follows: one is located under each fingertip, three under the palm, and two on the back of the hand. The type of actuator used is unclear. The hand pose is measured by an IMU in both products, the Gloveone uses flex sensors to measure the fingers position whereas the AvatarVR uses IMUs for each finger. As of March 2018, it is possible to order the products on the company website, but according to discussions on the forums, there are some problems with delivery.

The company Senso, based in the USA, has been working since 2015 on the "Senso Glove™" [7,8]. It provides interaction with 5 fingers, with one vibration motor under the last phalange of each finger. The measurement of finger and hand movements is based on inertial sensors. This makes the device cheap and easy to calibrate and ensures a high refresh rate, but at the cost of precision. Integrated pressure sensors measure the grip pressure. The Senso Glove comes in S, M, ML, L and XL size for men and S, M, L for women. As of March 2018, the second version of the product is available for software developers. The customer version is said to be 6 months late with respect to the company's website information.

Very recently, the German start-up company Cynteract has started working on a new glove concept for rehabilitation [9]. They are using a standard glove made of cloth, to which they add wires attached to servomotors, capable of exerting a force along the whole finger, in either opening or closing direction. The actuators and electronics are mounted on the forearm. The electronics of the glove measure not only the bending of the fingers but also the orientation in space, so that it is usable without an additional tracking system. The first prototypes are undergoing early clinical trials.

The Maestro glove from ContactCi (Cincinatti, US) [10] follows a similar principle. Five exotendons are connected to the same amount of servomotors assembled in a package that is mounted on the operator's forearm. The exotendons are routed along the upper body of the hand towards the different fingers. Embedded in a traditional glove they restrict the finger motions when fingers touch an object in the virtual reality environment. Five fingertip pads are responsible for vibration cues. 5 Flex sensors and the exotendon positions are being measured in the Maestro. Contact Ci is accepting applications for early beta testing, but does not give an indication when the Maestro will be released to the broader public.

3.2 Thimbles

By "thimble" a configuration with an actuator attached to a fingertip is meant. If it is possible to combine several thimbles in order to provide feedback on several fingers at the same time. In such way a function similar to that of a haptic glove can emerge.

The challenge in designing thimbles lies in the need to integrate sensors, actuators, a power source and a wireless transmission within a very light and compact device. In addition, the thimble needs to fit on fingers of different sizes without squeezing them painfully while avoiding the risk for slipping.

The device VRtouch™ of the French company GoTouchVR is a simple thimble with only one electromagnetic actuator, which applies pressure to the fingertip [11]. By means of a magnetic clip the thimble can be easily attached to the finger. Multi-finger touch is possible by mounting multiple devices on different fingers (3 per hand maximum). As with all thimble solutions collisions between modules prevent gestures where fingers are too near. The VRtouch™ supports Leap Motion and some other third party tracking systems to track the hand and finger. The product is available since November 2017 for software developers.

The company Tactai, based in the USA, also proposes a thimble called "Tactai Touch™" [12]. Based on 15 years of academic research, the device is able to render sensations of pressure as well as texture and contact [5]. A single thimble is said to weigh approximately 29 grams [5]. Again, software developers can purchase a kit, but Tactai has not yet announced a final release date for the consumer market.

3.3 Exoskeletons

An exoskeleton is an articulated structure which the user wears over his/her hand, and which transmits forces to the fingers. Because of the need to adapt to a variety of hand sizes and shapes, designers do not usually adopt the same kinematics as the fingers because it would require for each user a very precise adjustment of the segment lengths. Instead, the structure runs in parallel to the fingers on the outside of the hand. A number of intermediate linkages attach the exoskeleton then to the different phalanges of the hand.

The CyberGrasp™ is the most famous and the forerunner of all commercial exoskeletons [2,3]. The role of the very complex mechanical structure is to convey the force of a pulling cable to the fingertip without constraining the other joints. The movement of the fingers is not measured by the exoskeleton, but by a dataglove (CyberGlove) worn under it by the user. The maximum force (12 N) is large enough to stop completely the movement of a finger. However, the effect of having one's fingertips pulled backwards while nothing is happening on the phalanges and palm is very strange and not so convincing. Nevertheless, the company has been selling the device successfully for more than 20 years. Because of the high price and the very small number of available applications, the sales number have been low (about 2-5 pieces per year). Still, it is a serious achievement for a device that has been so much ahead of its time.

In the new generation of exoskeletons, the Dexmo™ by Dexta Robotics (China) has been highly anticipated, with its impressive design resembling a large claw [13]. The first prototypes used mechanical brakes to simulate the resistance of virtual objects [14], but the final version integrates servomotors for a variable force-feedback. The exoskeleton measures finger flexion and abduction, plus one rotation for the thumb. The force-feedback is limited to one degree-of-freedom per finger, with a maximum force of 0.3 Nm. The start-up Dexta Robotics has had a hectic course, after cancelling a first crowd-funding campaign. As of March 2018, only development kits are available, and highly priced (Table 1).

The US-based company HaptX Inc. has a very different and challenging approach. The design of the HaptX Glove™ resembles an armored glove, and the actuation principle is pneumatic [15]. The complete device features a smart silicon-based textile and integrated air channels that delivers high-resolution, high-displacement tactile feedback combined with a biomimetic exoskeleton for resistive force feedback. Magnetic sensors capture the finger movements with sub-millimeter motion tracking accuracy. The HaptX Glove includes more than 100 tactile actuators and delivers up to 22 N of force feedback. HaptX Gloves are focused on VR training and simulation applications for industrial users. Development Kit versions of the gloves will ship to select enterprise customers later this year.

The VRgluv™ is another exoskeleton coming from the USA. Also this glove looks like an armored glove [16]. The company announces 20N of force-feedback, high-frequency movement in 12 degrees-of-freedom and pressure measurement. Although the product developers are not releasing any technical details, apparently the exoskeleton is actuated by DC motors pulling cables. After a successful crowdfunding campaign closed in May 2017, the VRgluv team have not yet announced when production will be started.

The Dutch company Sense Glove is also busy developing an exoskeleton [17]. The first version used mechanical brakes and was entirely 3D-printed. This enabled the company to enter the market very quickly. The device applies unidirectional force-feedback on the finger flexion (in the direction of grasping), using one servomotor per finger pulling on a string, and can also apply vibrations. The maximum force is 7 N. A batch of development kits have been delivered in 2017, and the first small series production is announced for Summer 2018.

Finally, the French company Haption has demonstrated a prototype called the HGlove at several academic conferences and trade exhibitions (fig. 1) [18, 19]. Contrary to the other products, it provides interaction only for the thumb, index and middle finger. The device is attached to the hand via two straps with hook and loop fasteners around the palm and thumb. Two tiny DC motors apply a force on the fingertip through a two-bar mechanism with a reduction based on one gear and one small capstan. Consequently, the interaction works not only on the flexion/extension, but also on the rotation around the first phalange. The abduction is measured but no force-feedback is available on that movement. The maximum peak force is 12 N, and the maximum sustainable force is 5 N. It is possible to attach the HGlove to a force-feedback device such as the Virtuose 6D, which applies a force to the hand via a rigid fixation on the back plate of the exoskeleton. The HGlove is available for sale as single piece manufacturing. Haption does not plan production in series at this date.

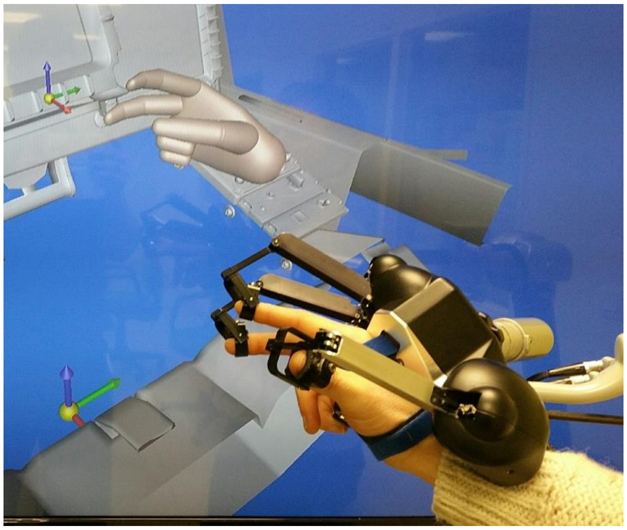

Fig. 1: prototype of the HGlove

Like most exoskeletons, one major difficulty in the implementation of the HGlove in Virtual Reality comes from the mechanical structure: because of the need to adapt to any hand size and shape, it needs a much larger workspace than the actual fingers of any particular person. Not only has Haption designed the structure with only two joints. where the human finger has three. The offset between the joints and the phalanges are large so that there is no correspondence between the joint angles measured by the motor encoders and the finger pose. One solution could be to have the user wear a dataglove, thus measuring the finger pose directly. The solution proposed by Haption is to describe a model of the hand and use inverted kinematics in order to calculate the finger pose. By measuring a few standard hand poses at the start, the system calibrates the model to the actual size and form of the user's hand within a few seconds.

4. Conclusion

As shown in Table 1, the actuation principles chosen by the developers of haptic gloves for commercial products tend to narrow down to a very limited number of solutions. Except for HaptX who relies on a smart textile with embedded air channels, which as a consequence implies that it cannot be made wireless, all other commercial systems are using traditional electromagnetic motors. This stands in contrast to the plethora of drive mechanisms that have been and are being explored by research teams worldwide [5]. Nevertheless, it appears that even with such proven technology, the designers experience considerable challenges to deliver the promised products in due time.

Table 1 - Overview of commercial haptic gloves

Device	Type	Nr fingers	Wireless	Actuator	Force-feedback	Tactile feedback	Hand tracking	Active DoFs	Weight (g)	Published price
Gloveone	Glove	5	yes	Electromagnetic	no	yes	yes	10	na	499 €
AvatarVR	Glove	5	yes	Electromagnetic	no	yes	yes	10	na	1100 €
Senso Glove	Glove	5	yes	Electromagnetic	no	yes	yes	5	na	599 $[1,2]
Cynteract	Glove	5	yes	Electromagnetic	yes	no	yes	5	na	na
Maestro	Glove	5	yes	Electromagnetic	yes	yes	yes	5	590	na
GoTouchVR	Thimble	1	yes	Electromagnetic	no	yes	no	1	20	na

Tactai Touch	Thimble	1	yes	na	no	yes	no	1	29	na
CyberGrasp	Exosk.	5	no	Electromagnetic	yes	no	no	5	450	50000 $[3]
Dexmo	Exosk.	5	yes	Electromagnetic	yes	no	no	5	320	12000 $[1]
HaptX	Exosk.	5	no	Pneumatic	yes	yes	yes	na	na	na
VRgluv	Exosk.	5	yes	Electromagnetic	yes	no	no	5	na	579 $
Sense Glove DK1	Exosk.	5	yes	Electromagnetic (brakes)	no	no	no	5	300	999 €[1,2]
HGlove	Exosk.	3	no	DC motor	yes	no	no	9	750	30000 €[3]

[1] Development Kit (DK)
[2] Two pieces (left and right)
[3] Single piece manufacturing

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