POLITECNICO DI TORINO

Master's Degree in Computer Engineering

Master's Degree Thesis

Providing force and vibrotactile feedback with haptic devices for simulating industrial tools in immersive Virtual Reality

Supervisors

Prof. Fabrizio LAMBERTI

Prof. Paolo MAGGIORE

Dr. Filippo Gabriele PRATTICÒ

Candidate

Matteo PIVIOTTI

October 2021

Summary

Virtual Reality (VR) is an emerging technology that, in recent years, has become more and more present in people's everyday life thanks to a reduction of hardware costs and an increased simulation quality. This technology could be used in different domains like the educational one, where the users can apply a learning by doing approach in different industry sectors: in fact, thanks to VR, a training procedure can be recreated in a safe environment, whereas in a real environment, an inexperienced user could cause damages to himself/herself and to the machine he or she is interacting with. The goal of VR is the creation of experiences that are as much realistic as possible and, in order to increase the sense of immersion, all the human five senses should be deceived; the sight could be easily teased thanks to a high-fidelity graphics rendering, and also the hearing can be deceived by a simulation that contains all the sounds that the user would perceive in a real environment. Unfortunately, regarding other senses, it is everything a lot more complex. Leonardo Aircraft is a company that strongly believes in eXtended Reality technologies and innovation. In the Department of Training and Simulation Systems, a VR experience related to aircraft maintenance, training and vehicle familiarization had been developed. Starting from a desktop application leveraging keyboard and mouse, the company has built a VR application. The first version of the application was based on the use of hand controllers for managing the interactions in virtual environment. However, this approach did not allow natural interactions with virtual objects, because the user had to press a button to simulate a grab or pinch. To solve this problem, the hand free approach was studied, but it required the user to have his/her hands in his/her field of view, otherwise the tracking could be lost; for maintainers that could be problematic because, often, the user needs to pick up objects without looking. Another drawback is related to the fact that the user cannot feel a virtual object while he/she is interacting with it because the technology used can only track the hands movements but it is not able to give a mid-air haptic feedback. A solution could be the usage of a mid-air haptic feedback technology like Stratos, offered by Ultraleap, but this approach would work only for stationary applications. In the case of Leonardo Aircraft, the user must be able to move himself/herself and to navigate a hangar. To overcome

these issues, in the present thesis, ManusVR gloves have been used: in this way the user can be notified when he/she interacts with a certain object and he/she can also perform operations without looking to the his/her hands in every moment. The type of this haptic feedback is binary: a pulse with maximum amplitude is rendered on each finger when the user grabs, pinches or releases an object. Starting from this binary feedback, through a collaboration with the VR@POLITO staff it has been decided to investigate a precise vibrotactile feedback in a screwing operation in different materials, and to study also if a force feedback could be useful in object manipulation and grasping tasks. The goal of this document is thus to report on the activities that have been carried out to compare two different haptic systems, namely, the SenseGlove Development Kit One and a system made up of a 3D printed mockup and the ManusVR gloves in two types of tasks: manipulation and screwing operations in different materials, i.e., wood and aluminium, focusing on passive haptic sensations related to gussets manipulation and drill grasping, and vibrotactile feedback related to screwdriving. The work started from the analysis of the state of the art in the field. Then, in order to recreate real sensations in VR, the waveforms generated using a real electric screwdriver have been captured during screwing operations in four different conditions: mid-air screwing, contact between the tip and the screw's head, tip reaching the end of the stroke, and the tip escaping from the screw's position. Afterwards, thanks to a scanner 3D, the mathematical model of the screwdriver was obtained, and modified in order to make it become a holder for an HTC Vive controller and build the mockup. The firmware for ManusVR gloves and SenseGlove DK1 was developed, in order to correctly render the waveforms that had been previously captured. In order to render the force feedback, it was written some code for SenseGlove, defining the force-displacement curve for each interactable object in the scene. For the other system, the 3D printed object intrinsically provides the passive haptic feedback thanks to the shape of the mockup. At the end of the development phase, some users tried a VR application that was created ad hoc to stress both the systems in the considered tasks. The users first tried to screw different types of screws, with different lengths, in different materials in the real world. Afterwards, they moved to VR. In the application, the user is immersed in a workshop and, after a short tutorial that is meant to explain him/her how to grab and move objects or how the instructions are given, he/she is guided by a virtual assistant which asks him/her to perform the tasks that were experimented in the real world. The user has to position correctly some gussets and then screw different screws focusing on haptic perceptions. After the experiments, all the users had to fill in a questionnaire that evaluates the usability of the application with the different haptic systems, the physical and mental workload, the overall fidelity of simulation with respect to the real experience and include some custom questions about the haptic sensations perceived. The results showed that both systems have been considered as usable, but for the manipulation task and fidelity of vibrotactile feedback, SenseGlove appears to be the better one. The mockup provides a better passive haptic feedback because it was able to better approximate the shape of a real screwdriver. This system also resulted as easier to wear and lighter because it is not composed by an exoskeleton. In the future, both systems could be improved. In order to make the system lighter and easier to wear, SenseGlove Nova could be used, whereas for what it concerns the mockup, it could be improved by adding some linear actuators in order to better approximate the real screwdriver. Finally, it could be interesting to implement the same simulation adding a thermal feedback by using the technology offered by WEART, which is based not on gloves, but on a ring: the user has to wear up to three rings per hand and he/she would thus be able to feel pressure feedback, vibrotactile feedback and temperature feedback on fingertip.

Acknowledgements

As I am an engineer I'm going to write also for the acknowledgements a bullet list below.

- Claudio: my dad was the person who believed in me and supported me right from the start. Over the years he has given me advice, encouraging me to continue dreaming, even when awake.
- Antonella: my mom, who supported me every day with a hug and a smile. Her philosophy is: it's the small gestures that make people great. Thanks mom, from the bottom of the heart of your "principino".
- Martina: She is the love of my life. She supported me everywhere and in all the circumstances.
- Ponza and Anto: They are lifelong friends, I wish to be able to spend a lot of time with them.
- Didi: My uncle, that supported me during this period.
- “I cugini ed il cuginetto in arrivo”: Carlotta, Andrea and ..... I really love you so much, thanks for the support!
- Paola and Davide: I wish to thank you for all the times that you cooked me the “polletto con alberelli verdi”, for let me taste the strongest chili in the world and for all the advice that you have given.
- I nonni: I know that you won't be able to read this document and not even to come at my discussion but they, even from far away, helped me.
- Luisa and Sigfrido: they believed in me since I was child.
- Massimo: He is my tutor in Leonardo Company, he helped me a lot with his advice. I wish to work with him in the innovation environment for a long time!

- VR@POLITO team: I'm grateful especially to Gabriele and Davide because they helped me a lot during this work.
- Leonardo team: especially thanks to Federico, Fabio, Daniela, Donato, Fabrizio and Francesco. They introduced me in Leonardo Company and allowed me to try amazing technologies.
- Camerana team: thanks to Cosimo, Roberto, Francesco and Raffaele for the support in the mechanical processing.

Table of Contents

List of Tables

List of Figures

Acronyms

AI
Artificial Intelligence

XR
Extended Reality

VR
Virtual Reality

AR
Augmented Reality

RT
Real Time

SW
Software

HW
Hardware

RHI
Rubber Hand Illusion

DOF
Degree of Freedom

SLA
Stereo lithography

LRA
  Linear Resonant Actuator

VTF
  Vibrotactile Feedback

FFB
  Force Feedback

RV
  Reality-Virtuality Continuum

DFT
  Discrete Fourier Transform

Chapter 1

Introduction

1.1 The sense of illusion

It has always been of great interest for technology developers to try to emulate sensations in a way that deceives the senses of the human people. In the history it can be seen how for example Thomas Edison was able to replicate a sound using his phonograph, or how the Lumiere brothers at the end of the 19th century reproduced a moving image. Many experiments were conducted to achieve results similar to those just mentioned in the world of touch, in order to recreate sensations such as: material texture, vibration and stiffness. The most famous certainly concerns the Rubber Hand Illusion (RHI): The body representation is composed of two fundamental elements: the sense of Body Ownership and the sense of Agency. The sense of Ownership is the feeling of belonging of our body which is always present and which is independent of whether the actions performed are voluntary or involuntary. The sense of Agency, on the other hand, is the feeling of having caused or generated an action. The RHI was used by Botvinikick and Cohen in 1998 to understand the Ownership's sense, in particular to understand if a rubber hand could be considered by our brain part of our body. Ten users participated at that experiment. Every person was asked to sit down and, in front of him/her, there was a rubber hand, which had the size similar to that of a real one; the real hand was hidden behind a panel as shown in Figure 1.1. The experimenters, by using a brush, touched, in a synchronous way the real hand and the one made by rubber. After 10 minutes the users were asked to complete a survey. The answers were surprising: the major part of the users, after the stimulation had felt the rubber hand as it was belonging to their body.

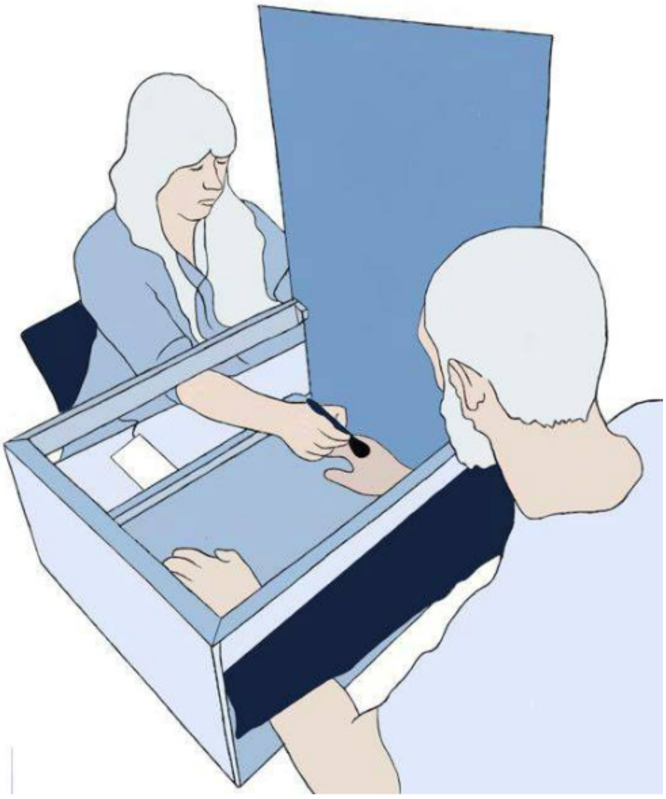


Figure 1.1: RHI experiment [1].

1.2 Haptic perception

The RHI experiment proves that sense of touch can be deceived, but if is compared to the other senses (taste, smell, hearing and sight) can be immediately deduced that the sense of touch is not localized in a specific zone of the body as it happens for the other four, but it is distributed across every part of the body, in particular in our skin, in our muscles and tendons. The literature typically categorizes the sense of touch in two sensations: kinesthetic and tactile. Kinesthetic sensations are like forces and torque and they are detected by our muscles and tendons; the tactile sensations are like pressure and vibration; they are sensed by mechanoreceptors.

1.3 Haptic devices

In order to provide haptic feedback, three main families of haptic devices (Figure 1.2) can be used. The first category is the graspable one: it is composed by different devices that could be grounded or not, and they can simulate in a precise manner the usage of a tool (e.g., screwdriver). The second category is composed by wearable systems, that are directly worn on the skin and can provide cutaneous sensations; they can have also an exoskeleton in order to provide a reaction against the user. The last category is composed by touchable devices; they are displays that can change their characteristics based on the finger location.

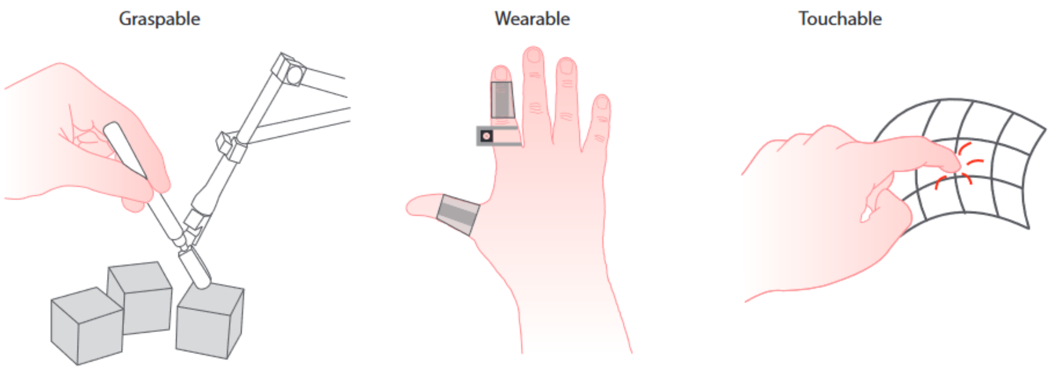


Figure 1.2: Different haptic devices [2].

1.4 Kinesthetic feedback

The kinesthetic feedback is the sensation related to movement and force. The receptors that allow us to perceive these sensations are those reported below.

- Muscle spindles: they are able to detect the length of the muscles and send these information to the brain via fibers.
- Golgi tendon organs: they are a kind of sensory perception that sense changes in muscle tension.

The Phantom Premium haptic device (originally commercially available from SensAble Technologies) was a milestone in the field, because it provides high forces in three degrees of freedom (DoFs) [3] (Figure 1.3).

1.5 Vibration feedback

People can distinguish over different vibrations, tactile sensations and pressures thanks to special kind of sensors called mechanoreceptors as can be seen in Figure 1.4. They work thanks to a mechanically-gated ion channels whose gates open or close in response to pressure. This action creates a different concentration in

Figure 1.3: Phantom Premium haptic device [4].

the two sides of the cell, and this causes an osmotic current that is traduced into electric potential and sent to central unit. The different classes of mechanoreceptors are described:

- Merkel Cells: they are sensible at the frequency that is less than 5 Hz. They are organized in Merkel cell–neurite complex: up to 90 Merkel cells are merged into one fiber.

- Ruffini Endings: they are located in the deep layers of the skin, and register mechanical deformation of the skin.

- Pacinian Corpuscle: they are sensible to high frequencies in range 40-400 Hz.

- Meissner corpuscle: they are sensible to transient stimuli in the range of 5-40 Hz.

1.6 Extended Reality

Extended Reality (XR) is an umbrella term that refers to Milgram's Continuum [6]. This concept can be summarized in the RV Continuum (Figure 1.5).

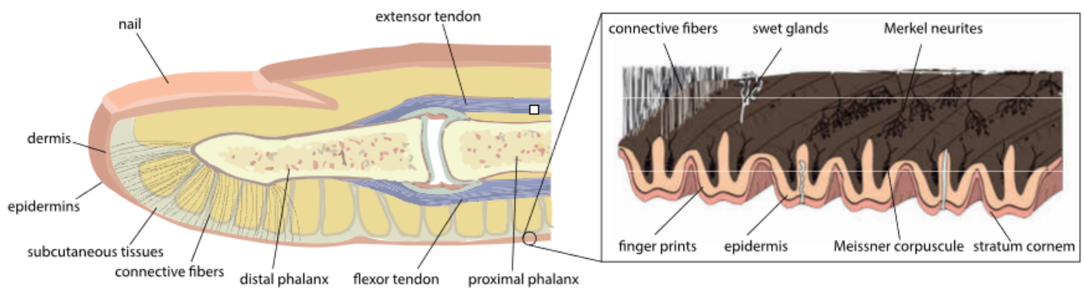


Figure 1.4: Finger anatomy [5].

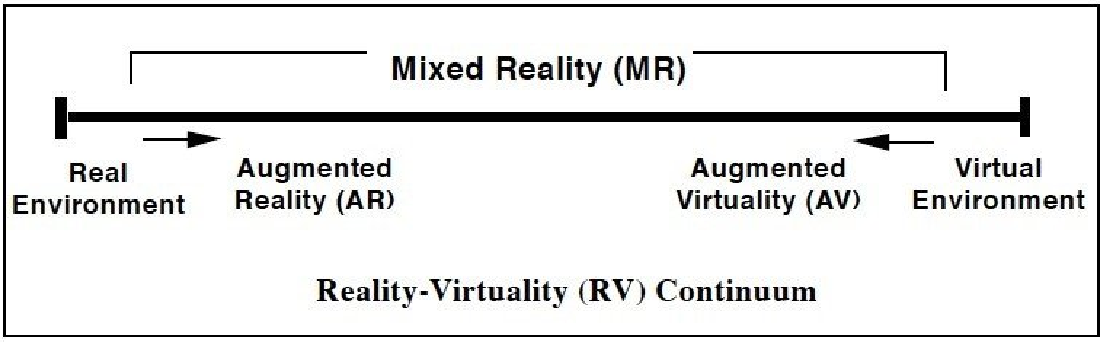


Figure 1.5: RV continuum [7].

This diagram represents the degrees of blending from real world (left most section) to the virtual environment (the right most section). In this work there will be the focus on virtual reality (VR). VR is a technology that is based on interactive simulation of a computer generated environment. There are two types of VR (Figure 1.6):

- Desktop: based on mouse and keyboard; it is cheap but has a low degree of immersion.

- Immersive: nowadays it is usually experienced through headsets; it allows a greater deceiving sensory stimulation with respect to desktop one, but usually it is expensive.

(a) Immersive VR. (b) Desktop VR.

Figure 1.6: The leftmost figure is immersive VR, the rightmost is desktop VR [8].

The term "Virtual Reality" was used for the first time in 1982 by Damien Broderick in the science fiction book "The Judas Mandala". Before developing today's hardware some steps have been done in the history. In 1962 was created a passive motorcycle simulator called Sensorama, which could provide tactile feedback and also olfactory feedback. In 1968 Ivan Sutherland built the first stereoscopic HMD, and in 1987 there were built the first commercial data gloves. In the 90's it happened that there was a loss of interest in VR for three factors, listed below.

- Computational power: the hardware at that time was not able to provide the necessary computational power for a real-time simulation with high visual fidelity graphics.

- Software/libraries: there was no software for managing the complexity of virtual environment, because it is necessary to manage not only the graphics rendering but also the physic computation.

- Low-res interfaces: the user experience was poor due to the quality of interface (e.g., display).

But then, as it can be seen in Figure 1.7, the interest in VR started to grow thanks to the factors listed below, as testified by the marked share.

- GPU improvements: millions of polygons could be texturized in a second.

- Availability of software/libraries: physics engines, software for performing audio management and 2D/3D content creation.

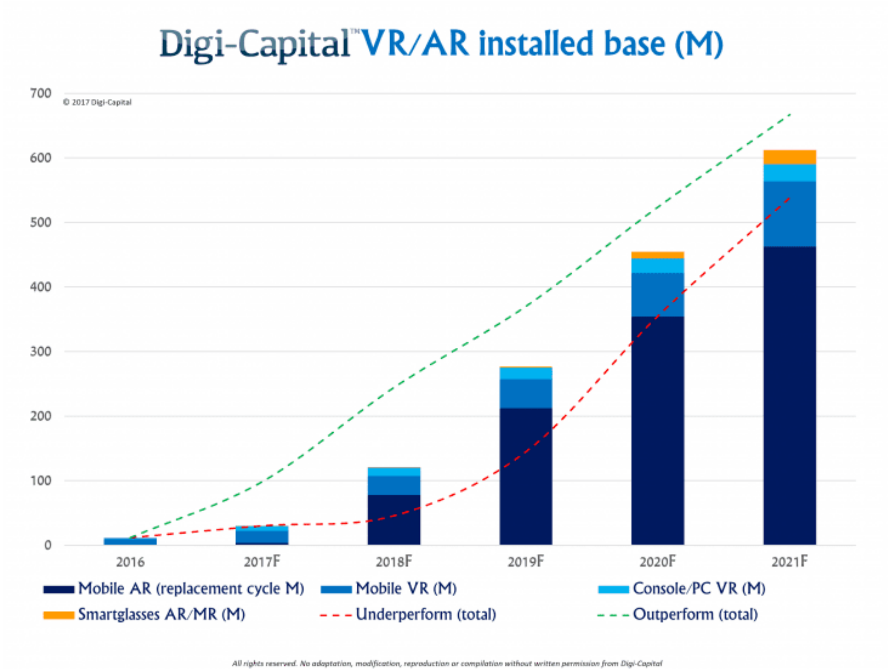


Figure 1.7: VR trend [9].

Since VR enables realistic experience thanks to high fidelity graphics rendering it should be important to reach the same level of simulation fidelity for somatosensory system, that is responsible for the reaction of the body with respect to external stimuli (e.g., vibration or forces). In order to increase the realism of perceived features and to enhance the naturalism of manipulation, different kind of controllers are used. In Figure 1.8 two different types of controllers are presented but this kind of hardware has three main drawbacks that are listed below.

- Unrealistic interactions: the user interacts with virtual environment in a way usually not natural, because he/she has to use buttons for picking up an object.

- Limited haptic capabilities: they can render a VTF that is shared among all the fingers.

- Only one passive FFB: they can only render passive force feedback due to their own invariant shape.

(a) HTC Vive controllers.

(b) Valve Index.

Figure 1.8: Two different controllers: on the left HTC Vive, on the right Valve Index.

Nowadays different devices are built including haptic gloves that have higher performances and are responsible for an higher potential with respect to traditional controllers. In Figure 1.9 an example of different haptic gloves can be seen.

(a) HaptX glove.

(b) SenseGlove Nova.

(c) Bebop.

Figure 1.9: Three different controllers: on the left HaptX gloves [10], on the center SenseGlove Nova gloves [11], on the right Bebop gloves [12]

This kind of hardware has intrinsically two main advantages with respect to controller:

- the vibrotactile feedback (VTF) is rendered on each finger and it allows an higher simulation fidelity;
- the force feedback provided (FFB) could be updated in real time: this allows the user to feel different object shapes and materials (stiffness).

Starting from the benefits of the haptic gloves and a real maintenance scenario, in this work it is created a VR application based on a screwdriving procedure: the user has to place different gussets in the correct position and then he/she has to screw three different screws, with different lengths, in the aluminium and three different screws, with different lengths, in the wood. In order to perform these tasks he/she has to use two configurations that are described below.

- Configuration based on SenseGlove DK1: this kind of hardware is based on gloves which provide, thanks to ERM motors, VTF and FFB.

- Configuration based on ManusVR and 3D printed mockup: this solution is composed by two different parts: the ManusVR gloves are used for fingers tracking; instead the 3D printed mockup is for providing a passive FFB. The VTF is provided by the HTC Vive controller.

These configurations are chosen for this work because both are able to provide VTF and FFB. The first one is different from the other in VTF rendering because the number of motor and the type is different with respect to the second one. Also these configurations differ in FFB rendering: the first one, thanks to different wires, blocks the user's finger in a specific position when a collision happens in VR, in contrast the second configuration is able to render forces thanks to the shape of 3D printing screwdriver. During the VR experience the user has to perform two different kind of operations that are listed below.

- Gussets manipulation: the user has to grab gussets and place them in the correct position (Figure 1.10).

Figure 1.10: The user is holding a gusset in his/her hand.

- Screwing operation: the user, by using an electrical screwdriver, should screw the correspondent screw (Figure 1.11).

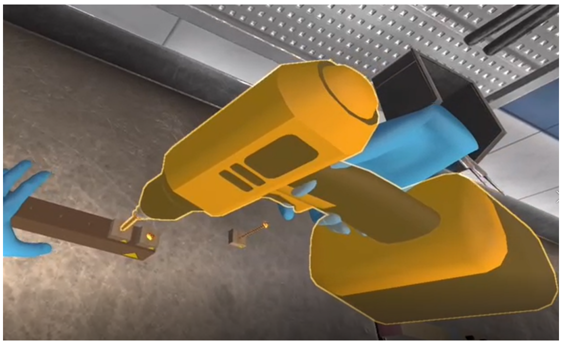


Figure 1.11: The user is performing a screwing operation.

A user study was conducted in order to evaluate the two configurations. Objective and Subjective data were collected to evaluate the following features:

- Usability;
- Physical and mental workload;
- Haptic perception.

The structure of this work is divided in different chapters listed below.

- Chapter 2 describes the state of the art about VR, the haptic technology and the different classes of haptic devices are presented.
- Chapter 3 presents the main technologies used in this work are presented.
- Chapter 4 specifies in detail how the application is implemented.
- Chapter 5 explaines how the tests are designed.
- Chapter 6 reports the results of tests.
- Chapter 7 provides the conclusions and future works.

Chapter 2

Technologies

In order to create the two configurations and the VR experience different hardware and software are used. In this chapter the main technologies are described.

2.1 ManusVR system

In order to create the configuration based on gloves and 3D printed mockup, it is used the ManusVR system, that is composed by two gloves, one for each hand. Inside each glove (Figure 2.1) are embedded five flex sensors, which are used for estimate the correct positions of finger joints. Each fingertip has got a Linear Resonant Actuator (LRA) vibration motor in order to provide haptic sensations. The motor used for providing haptic feedback belongs to the LRAs family. The work principle is based on the motion of internal magnetic mass attached to a spring; the motion is caused by an electrical signal through the LRAs coil. This system, that is composed by a mass and a spring, oscillates with a greater amplitude in correspondence to a particular frequencies. The bandwidth and energy loss are described by quality factor. A low quality factor means a wide bandwidth and higher rate of energy loss, in the case of LRAs motor the quality factor is high and that means low rate of energy loss but a very small bandwidth. In Figure 2.2 the internal structure of a LRA motor can be seen. The position of the hand can be estimated thanks, i.e., to a SteamVR tracker that can be mounted, by using an appropriate adapter, on the wrist. The connection between ManusVR glove and SteamVR tracker can be made thanks to Polygon [15] that is a full body, six points inverse kinematic solver. In particular it takes the position and orientation of six body parts and estimate where the rest of the body is. This feature is fully compatible and plugplay with Unity (Section 2.3). To use Polygon the features listed below are needed.

- Manus dongle with a valid Polygon license.

Figure 2.1: ManusVR glove [13].

- trackers;
- Windows 10;
- 8GB RAM;
- GTX 1060.

In Figure 2.3 Polygon in action can be seen. The tracking is based on SteamVR trackers; the user has got two trackers for the hands, two trackers for the feet, one tracker in the belt position and the headset.

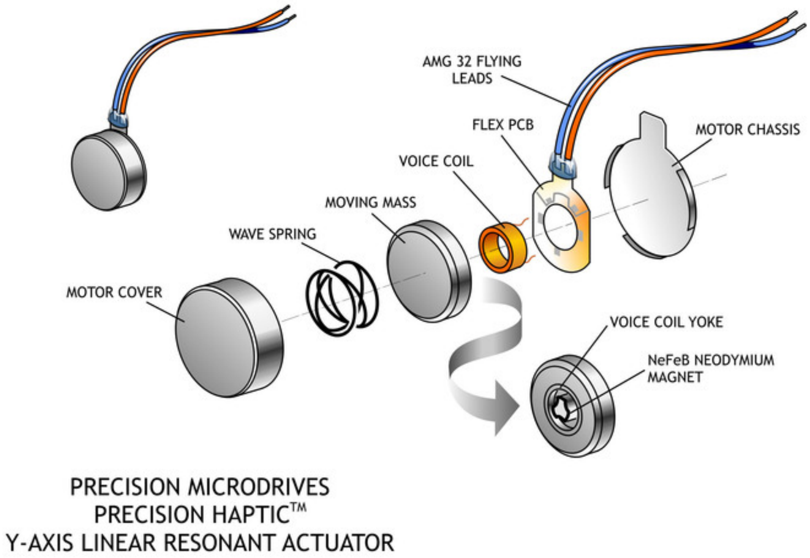


Figure 2.2: LRA motor structure [14]

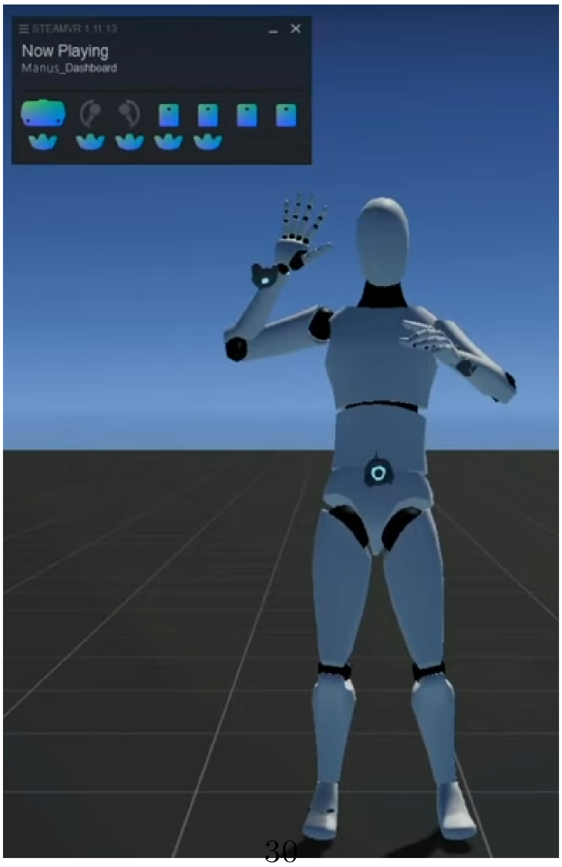


Figure 2.3: Polygon [15].

ManusVR gloves are used with the 3D mockup in order to create a system with which the user can interact during the virtual reality experience. The ManusVR gloves in this context are used for the fingers and hands tracking, intstead the haptic and passive FFB are generated, respectively, thanks to HTC Vive controller and 3D printed mockup (Section 4.5).

2.2 SenseGlove

In this work the SenseGlove DK1 (Figure 2.4) model is used for providing both haptic feedback, FFB and also tracking. Its principle of FFB is patented: there is an exoskeleton that is composed by a series of linkages concatenated through joints; thanks to this structure the user's fingers are stopped when a virtual object is encountered in virtual environment. The maximum force that this hardware can render is 40 N per finger [16].

Regarding VTF, the glove has six actuators, one per finger plus one bigger inside the palm. The motors type are different then LRAs. in fact, ERMs are used in this case (Figure 2.5). ERM is the acronym for Eccentric Rotating Mass, a DC motor with an off-centre load attached to the shaft. When the motor is switched on, a centripetal force is created due to unbalanced mass.

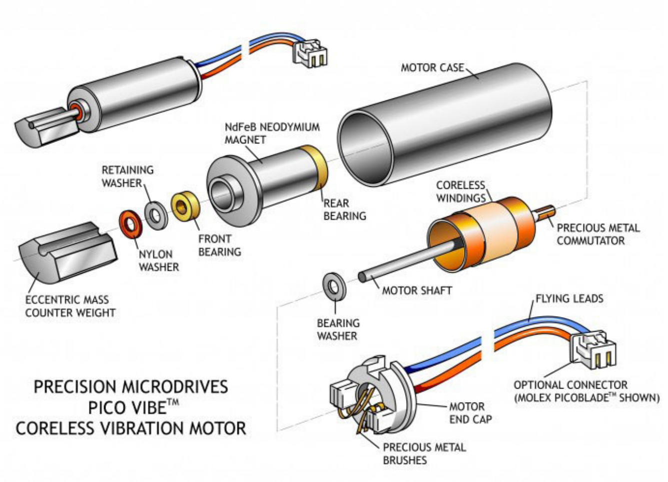


Figure 2.5: ERM motor [17].

In order to calculate rotation frequency we have to consider the RPM (Revolutions Per Minute): $Hz = RPM/60$.
In Figure 2.6 it is described how are correlated amplitude, frequency and voltage in ERM motors; in particular, the major difference respect to LRAs is that in

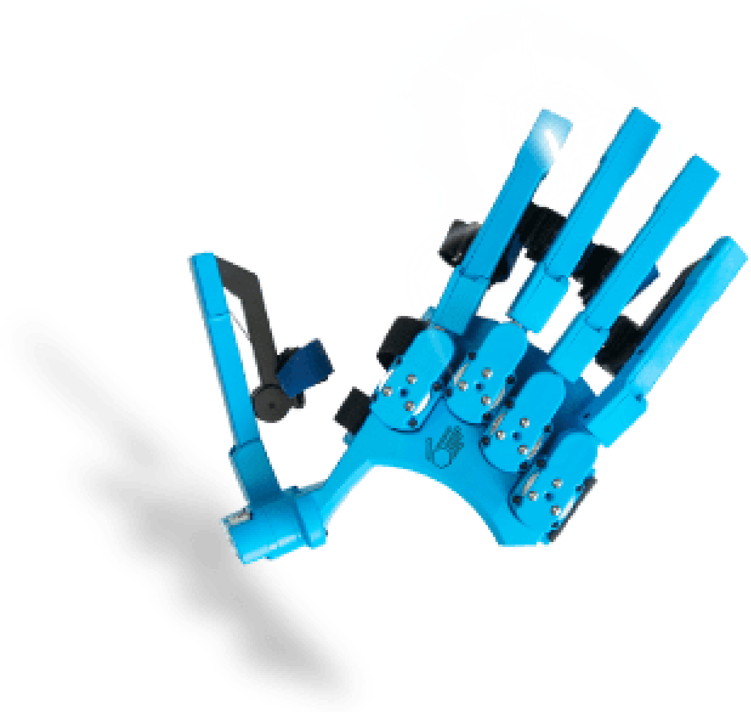


Figure 2.4: SenseGlove DK1 [11] .

this case there is not a peak of resonant frequency but the frequency is strongly dependant on driven voltage.

2.3 Unity

Unity is a game engine that allows the creation of multi platform experiences, in this work it was used for building the VR experience (Section 4.9). It could be used under different operating systems:

- Windows;
- macOS;

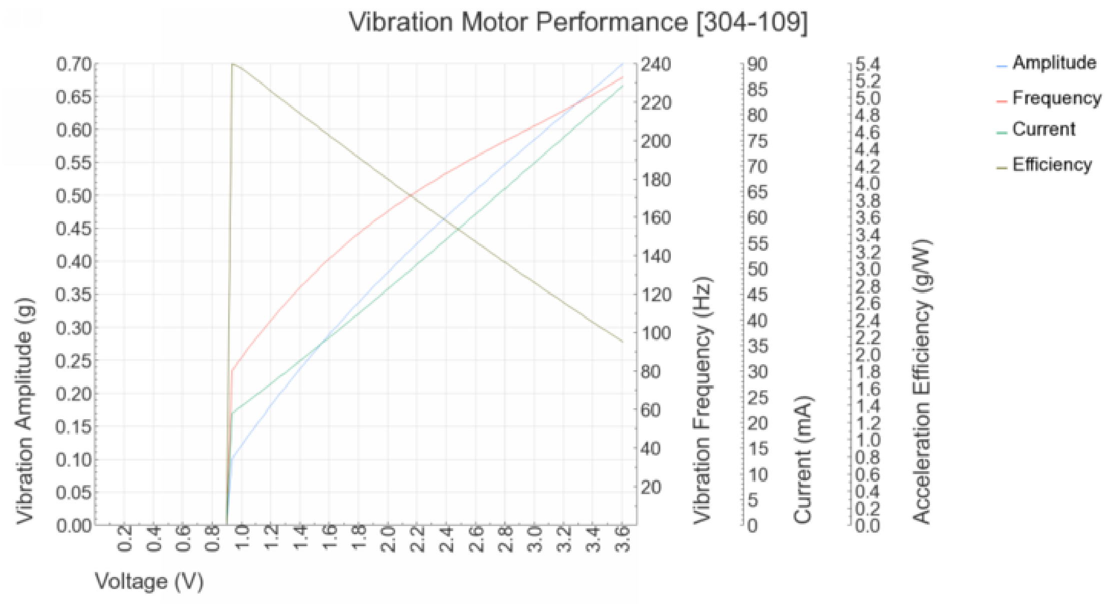


Figure 2.6: Characteristic of ERM motor [17].

- Linux.

The interface of the game engine is intuitive as it can be seen in Figure 2.7. In particular four main panels could be seen.

- Hierarchy: here all the GameObjects presented in the scene are displayed.
- Scene: here the user can move all the GameObjects and can build the whole scene.
- Game: when the user plays the application that he/she has created he/she has to use this panel.
- Asset Store: this panel can be used for the navigation inside the store; here the user can find some contents (environments, 3D models, functions, etc...) that can be purchased.
- Inspector: here all the components of a certain GameObjects are displayed. A component associates a certain behaviour to a GameObject: for example in Figure 2.7 the GameObject is named “Main Camera”, and has three components that define its behaviour, listed below.
  - Transform: it is used to store and manipulate the position, rotation and scale of the object.

  - Camera: it is used for capturing and displaying the world to the player.
  - Audio Listener: it is used for managing audio in the scene.

- Console: this panel is used for displaying all the information about what is happening in the experience

- Project: this panel contains all the folders that compose the Unity project.

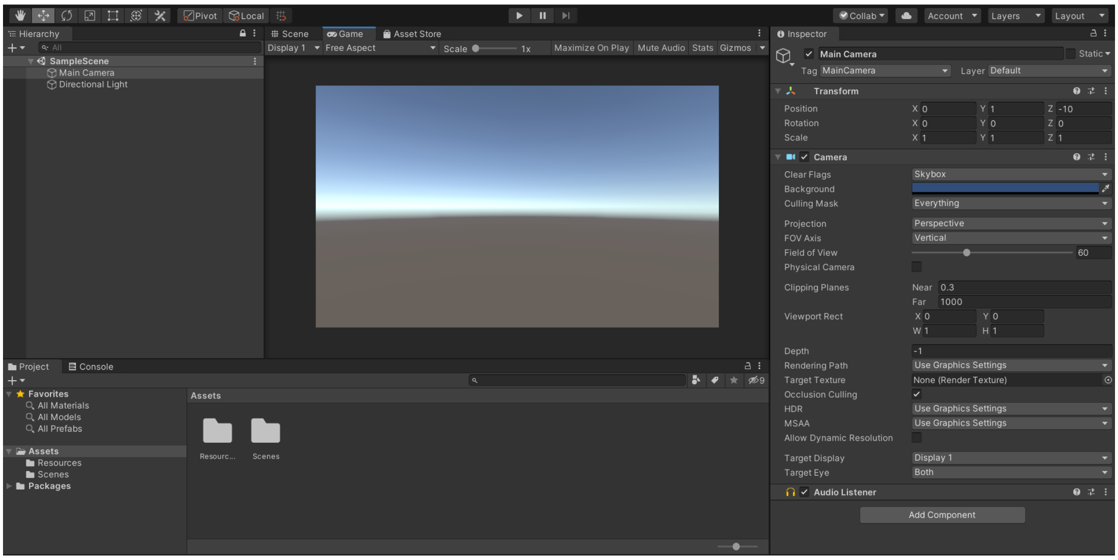


Figure 2.7: Unity interface.

2.4 HTC Vive

The HTC Vive is a VR ecosystem (Figure 2.8). It is composed by three main components.

- Headset: it has a resolution of 1080×1200 pixels per eye, with a refresh rate of 90 Hz and field of view of 110 degrees.

- A pair of controllers: they allow the user to interact with the virtual environment and are responsible for providing haptic feedback.

- A pair of base stations: enable an area up to 3.5×3.5 m to support 6 DOFs thanks to the emission of pulses that interact with controllers and headset with a sub-millimeter precision. They are based on Lighthouse system that is used for tracking position and orientation of headset and controller in realtime.

The ecosystem just described is used for the experiments (Chapter 5).

Figure 2.8: VIVE ecosystem [18].

2.5 3D Printing

The first 3D printer was created by Chuck Hall back in 1986, it worked by using a focused beam of ultraviolet light to harden thin levels of a resin in a successive manner; this process is called Stereo lithography (SLA) and it is the most used technology today. He also invented the STL files, that are a format for 3D printed designs. The most existing manufacturing technologies, such as CNC machining, create objects by starting with a large block of material and using a tool to cut pieces away until it is obtained the desired object . In contrast, 3D printing is an additive manufacturing process. Instead of subtracting away from an existing piece of material, 3D printing starts with a blank slate and then adds materials to it. The head of printer is driven by microcontroller along three different axis. There are three main 3D printing technologies, illustrated below.

- SLA: the objects are created by using a beam of high intensity light in order to harden a resin. This technology creates small objects, with high resolution (25 μm/layer), but they can be broken easily. An example of this printer could be seen in Figure 2.9.

Figure 2.9: Formlabs printer [19].

- SLS: it is the acronym for Selective Laser Sintering, the work principle is the same to the SLA, but here the beam is used to harden a powdered material. It creates objects with a resolution similar to SLA but also very strong; this approach could be used to create also metal structures with high precision. An example of this technology is in Figure 2.10.

Figure 2.10: Blueprinter-M3 printer [20].

- FDM: it is the acronym for Fused Deposition Modeling. It is the most used technology for prototyping and it has a resolution of (100 μm/layer). An example of this technology can be seen in Figure 2.11.

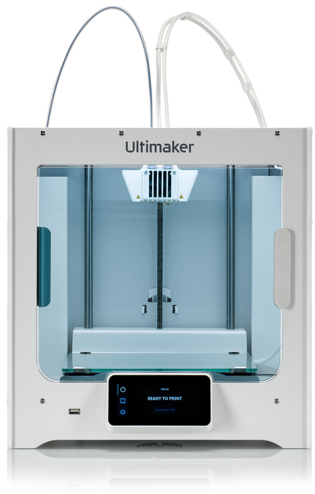


Figure 2.11: Ultimaker-S3 printer [21].

The FDM technology creates final objects by softening process of thermoplastic, that could be of two different types.

- ABS: it is the acronym for Acrylonitrile Butadiene Btyrene, it is made from petroleum, for example a LEGO piece is made by ABS.

- PLA: it is the acronym for Polylactic Acid, and this is made from corn.

The two materials share different properties:

- same melting point;

- variety of colors;

- cheap;

- low flexibility.

In Figure 2.12 the body of the LEGO is made by ABS, whereas the haptic gloves and the headset are home-made in PLA.

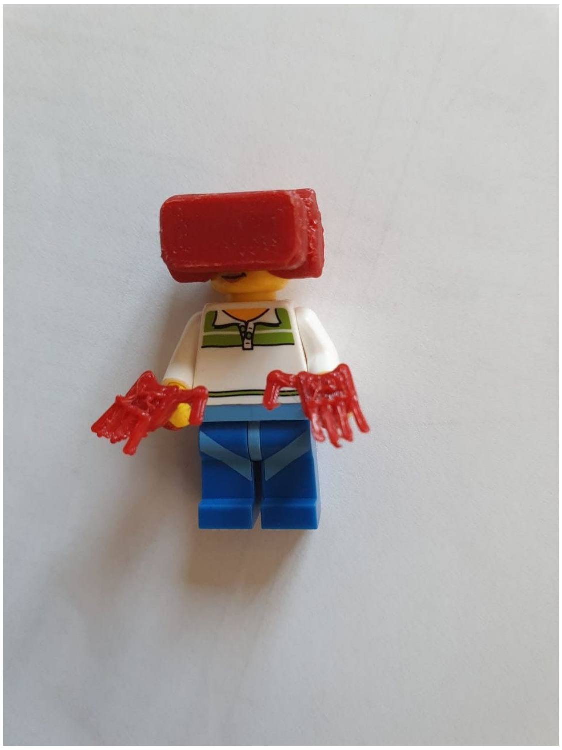


Figure 2.12: The body is made by ABS, whereas the headset and the gloves are made by PLA.

The technology just described is used in this work in order to create a physical mockup: since the goal of this work is to create a passive haptic with VTF, starting from the scanning of a real screwdriver it is then created an holder for HTC Vive controller that is used for generating passive haptic feedback as described in Section 4.5.

Chapter 3

State of the Art

In the following sections an investigation about the state of the art is provided: staring from the VR till the haptic feedback and the different families of haptic devices.

3.1 Virtual Reality

VR is a promising technology and it is very useful for the training purpose because, often, a real world training system suffers from three issues [22] :

- time consuming for preparing the environment for a real training;
- expensive to prepare the system and to hire the people for training;
- difficult to train people on emergency situations (e.g., fire prevention).

This technology could drastically reduce the costs for training, keeping the user in safety conditions. In order to create a training procedure it is necessary to follow three steps, described below.

- Task analysis: the goal of this step is to understand all the important aspects of a procedure.
- Training scenario sketching: the purpose of this step is to obtain a description of how the users perform specific task.
- Implementation:

In the military sector a lot of training scenarios have been created. In 2009 [23] has been created an application for U.S Navy, in which the user has the opportunity to learn to be a better sailor. The VR is used also in the Aviator Training Next

Program [24], in which it has been demonstrated that people that had a training on VR simulator reaches the same performances compared to the pilots that has been trained on real aircrafts. In [25] it is presented an application for training the French Army on the FELIN wapon calibration (Figure 3.1). Also in this case the VR training is efficient as the real one.

Figure 3.1: FELIN system [25].

Another training example where the VR technology could be applied is the ski teaching. For instance, in [26] it is presented an indoor simulator that helps the user to copy the virtual instructor's movements (Figure 3.2). The system was evaluated by testers in a positive way, but the drawback is the cyber sickness, especially for the vertical movements; this issue could be partially solved by reducing latency and trying to predict the user's behavior.

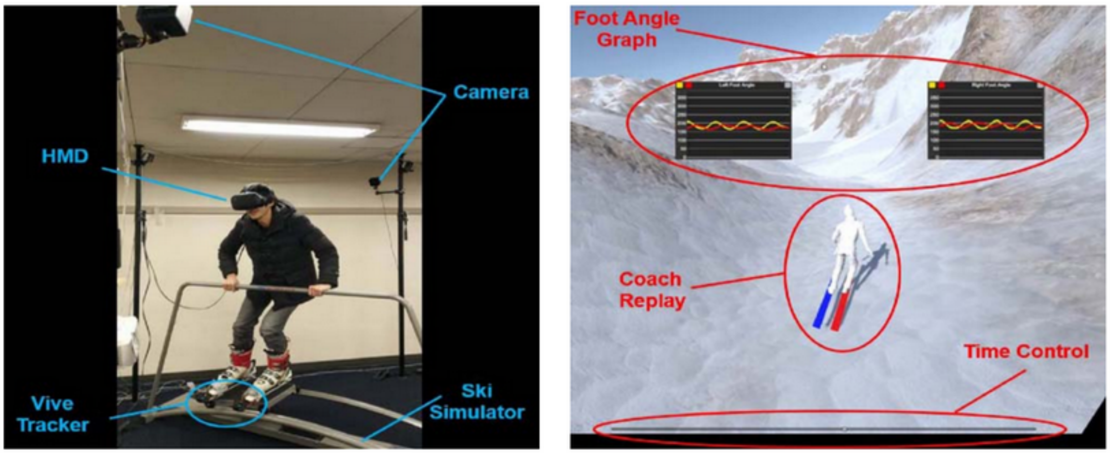


Figure 3.2: On the left the system in [26] , on the right the VR simulation.

It might be interesting to compare the VR teaching methodology with traditional approaches composed by slides and reflections. For instance, this was done in [27]:

the system that is used is a low-cost immersive VR platform and it is evident that this kind of methodology produces many benefits with respect to traditional one.

3.2 Haptic feedback

Nowadays VR application are mostly based on graphic rendering and on audio synthesis, but the haptic perception, commonly called sense of touch [28], often is not considered. This sense of touch can be categorized [29] [30] into the kinesthetic and the tactile senses, the first one is related to torque and forces; in contrast the other is based on the contact between skin and surfaces [28]. The haptic effect can be generated by particle jamming, as shown [31]. This phenomenon happens in granular materials: the particles combine themselves in order to generate a structure that is stronger than the one at the initial state. This property can be used for creating haptic sensations. The authors created a device like the one in Figure 3.3 which, by controlling the input pressure and the motor parameters (frequency and amplitude), can create softness, vibrations and textures.

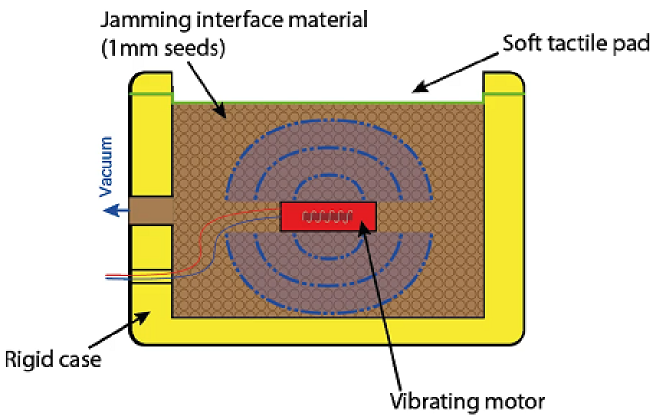


Figure 3.3: Device based on particle jamming [31].

It is important to underline that the haptic feedback could be transmitted far away from actuators and could be localized on a certain point. For instance, in [32] a soft haptic interface, made by gelatin and piezoelectric actuators, has been create in order to achieve this purpose.

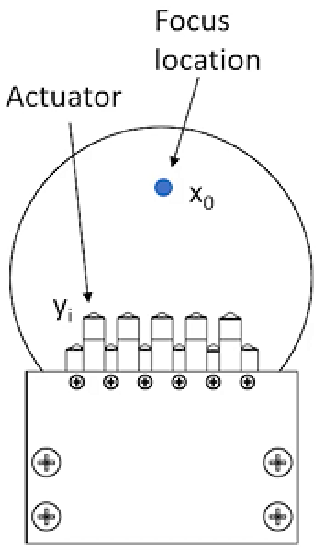
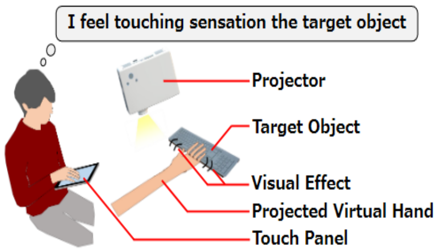


Figure 3.4: Soft haptic interface [32].

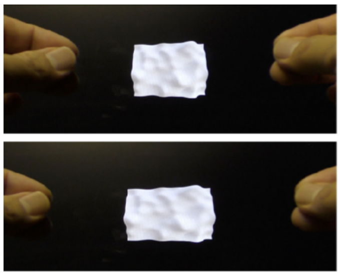
The haptic feedback could be transmitted not only by vibration motor, but also with an hydraulic systems. In [33] it is created a 3D printed system (Figure 3.5), which works thanks to the pressure that is transmitted from the fingertip to the tactile surface that is responsible for the haptic feedback.

Figure 3.5: Hydraulic haptic feedback [33].

It is also possible to simulate haptic feedback by using something called pseudo-haptic. This approach simulates haptic perception but is based on auditory feedback or visual feedback. In order to reach a good results the visual and haptic information must be coherent. For example in [34] it is presented a pseudo haptic system for texture simulation by using visual effects. A finger passes on a keyboard and the user, thanks to visual effects, can perceive the sensation of haptics. Another work [35] uses mid-air interaction for manipulating a virtual piece of paper. Also in this case, thanks to a visual effect the user is able to perceive haptic sensations. Of course this approach is interesting and doesn't require a specific hardware, but the level of immersion is lower compared to traditional haptic simulation approaches.



(a) Texture simulation.



(b) Piece of paper manipulation.

Figure 3.6: Pseudo haptic experiences: on the left a texture simulation, on the right the manipulation of piece of paper [35].

3.3 Haptic interfaces

The haptic interfaces taxonomy lists five different types [36] that are described below.

- Handhelds: they are typically held in hand and similarly to a controller. Thanks to the advent of VR for commercial purpose this type of devices become very popular in the last years. In fact they have a price that is low and they can provide vibrotactile perceptions. During the years a lot of studies have been proposed in order to provide different sensations with an handheld device: in [37] it is understood that the amplitude and the perception of the strength are strictly connected and the granularity and timbre of the signal were used to create distinct experiences; in [38] it is presented an haptic link (Figure 3.7) that is used for linking two HTC Vive controllers; it was useful because it can create a variable stiffness in double hand interaction (e.g., a fire gun), thanks to a chain made by balls, a socket and a cable that could be bulled by linear actuators. This technology has two main limitations:
  - it cannot provide inertial FFB;
  - due to mechanical characteristics this solution is heavy and limits the user's movements.

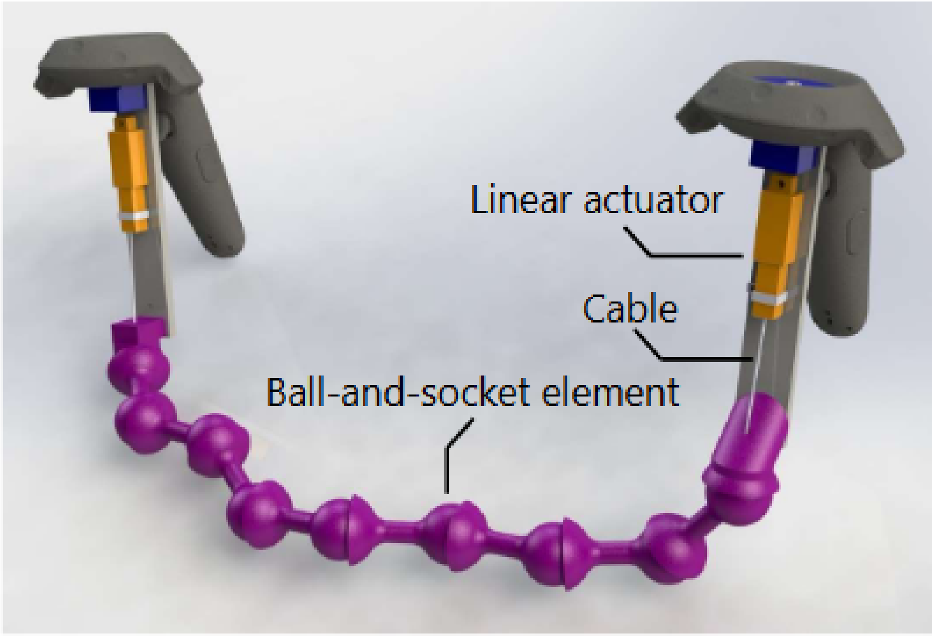


Figure 3.7: Haptic link [38].

In [39] two haptic VR controllers are presented: *NormalTouch* and *SenseTouch*. The first one is used for the FFB perception: its platform is actuated by three servomotors, which are used for replicating the orientation of the object in the virtual environment. The *SenseTouch* is made up of 16 pin arrays that allow the user to feel a texture inside the virtual environment. In Figure 3.8 the two controllers are displayed. The limitation of these technologies are:

- *NormalTouch*'s inability to render angles and corner;
- *SenseTouch* is bulky and complex with a limited pin resolution;
- both the devices are noisy during the experience.

Figure 3.8: On the left the *SenseTouch* controller, on the right *NormalTouch* controller [39].

In [40] the *Revolver* device is presented: it is composed by actuated wheel that is able to render different shapes and textures to the user when he/she touches a surface in VR. As it can be seen in Figure 3.9 the device can be used for rendering different surfaces and also for representing the corner and edges: in the leftmost image the wheel allows the user to perceive the blue surface, in the center of the image the edge is rendered and in the rightmost the black surface is rendered. It is important to say that the wheel can be substituted by another with different texture or pattern. A limitation of this device is that the people's hands do not have the same size and so it could happen that the physical contact happens before the virtual one and the result is the loss of realism.

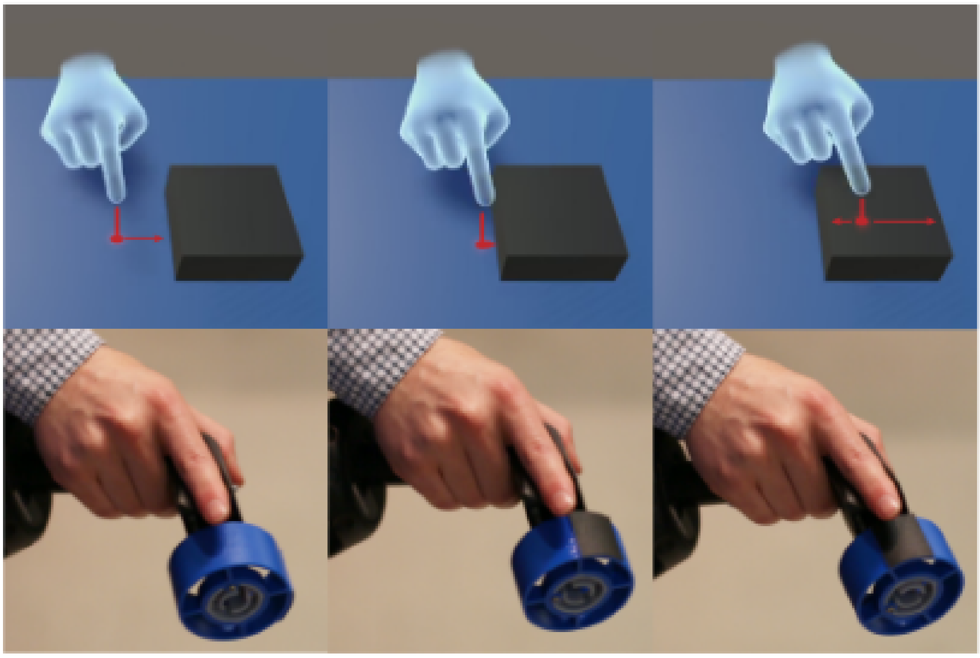


Figure 3.9: The *Revolver* control in three situations [40].

In [41] it was presented a new type of controller that is able to provide three different sensations to the user: grasping virtual objects, touching virtual surfaces and triggering. The different modality is based initially on the thumb position (Figure 3.10). If the thumb is on the side of the thumb rest and if the user holds a gun in the hand then the modality is *gun*; if the user has the thumb on the thumb rest side but does not have a gun in the hand then the *graspingmode* is enabled. If the thumb is not on the thumb rest the *touchmode* is used. In general this device is usable both in VR and in AR, but it suffers from the following limitations:

- the design is only for the right hand, not for the left one;
- it is not wireless because the wires are needed for power supply and communication;
- the impact of the hand size is relevant to the performance.

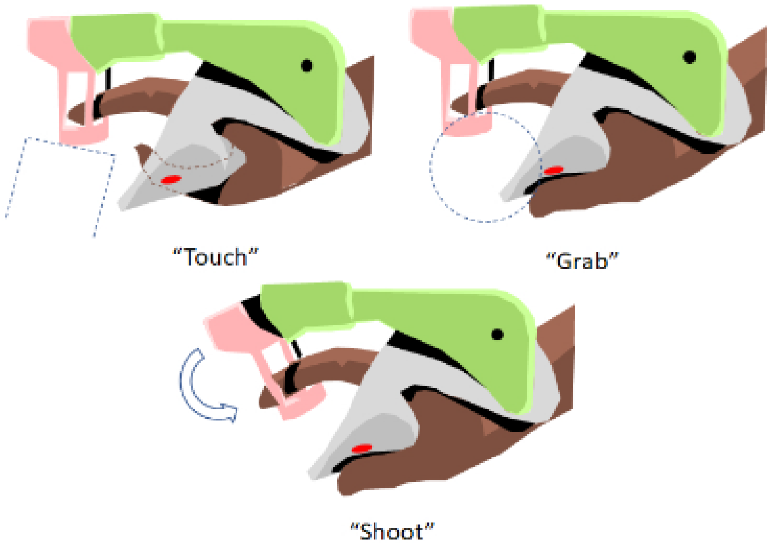


Figure 3.10: Position of the thumb with respect to the device [41].

The authors of [42] proposed a new devices, namely *TORC* (Figure 3.11). It allows the objects manipulation by using a thumb and other two fingers. This device uses vibrotactile motors in order to produce haptic sensations. This solution allows a very precise manipulation, but not all fingers are considered: in fact a user can only use thumb, index and medium to manipulate an object and cannot use other fingers or two hands manipulation. Also the size of the object that has to be manipulated is important: with a big object the system cannot be used.

Figure 3.11: *TORC* device [42].

In work [43] the *Drag : on* controller is created (Figure 3.12). It could generate dynamic passive feedback by changing its surface during interaction: when the user is manipulating an object he/she moves the controller and, since the *Drag : on* device could change its surface, the user perceives a different air-based haptic feedback. This device has two main limitations:

- the fixed orientation of the fan plane: if the controller's movement is parallel to the fan, the haptics does not work;
- high noise during interaction.

Figure 3.12: *Drag : on* device in different configurations [43].

In work [44], a tactile pin array is inserted into the handles of controllers, creating *HaptiVec*. This array is used for perceiving directional pressure in the eight cardinal directions. The device presented is compact and light; the users, thanks to *HaptiVec*, are able to distinguish between different cardinal directions with an accuracy of 79%.

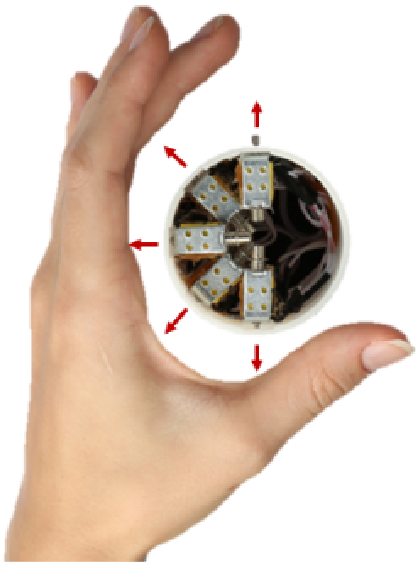


Figure 3.13: *HaptiVec* [44].

- Wearables: these devices must be worn by the user and so they should be light and comfortable. In [45], the *Wolverine* device (Figure 3.14) is created: it is used for the grasping simulation of a rigid object in VR. The system has low power consumption and low weight, but has some limitations:
  - types of objects with which it can interact;
  - the range of dimensions of virtual object are 20-160 mm;
  - this kind of structure could generate involuntary FFB.

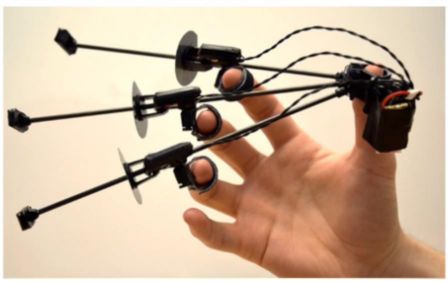


Figure 3.14: *Wolverine* device [45].

In work [46] the *FinGAR* device (Figure 3.15) is developed. It should be worn by three fingers: thumb, index and medium. It is composed by two main components listed below.

- DC motor: used for high frequency rendering and lateral skin deformation.
- Electrode array: used for providing pressure and low frequency perceptions.

Figure 3.15: *FinGAR* device [46].

In [47] the *Tasbi* device is developed (Figure 3.16). It is a wristband that is able to provide squeeze andVTF thanks to motor that has inside. In this work the haptic feedback is not given on the fingertip, but on the wrist and it could cause a poor quality of the feedback because it is not localized on the fingertip where the major of mechanoreceptors are present.

Figure 3.16: *Tasbi* device [47].

In [48] the *HRing* device is developed. It is used for creating an illusion of holes, bumps and it is able to make an object to be felt by the user softer or harder. It is composed by three component listed below.

- Two servo motors: they can rotate in the opposite direction or in the same direction. In the first case they can drive the belt up or down creating a pressure perception on the finger, in the other case the skin stretch sensation is created.
- Velcro strap band: it is used for fixing the device on the finger.
- Belt: it is the component responsible for the sensation perceived by the user. It is connected to the two servo motors.

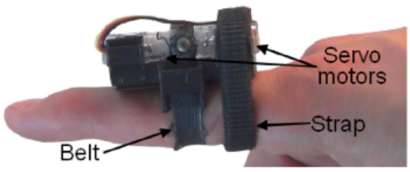


Figure 3.17: *HRing* device [48].

The limitation of this solution is the position of the strap band: it is not situated in the fingertip where the major part of mechanoreceptors are located. All the devices that are mentioned do not allow to feel obstacles like wall. To overcome this issue in work [49] it is presented *Wireality*, a device that arrests, thanks to a wires system, in a very accurate way, the fingers in correspondence of an hologram in VR. This system has two main drawbacks:

- can only create forces that are perpendicular to the user;
- it is impossible to grab small objects like a pen.

Figure 3.18: *Wireality* device [49].

- Encountered types: the goal of this technology is to provide a natural haptic feedback without controllers or wearable devices. This type of devices are able to provide a custom feedback based on user's needed. In work [50] a system (Figure 3.19) is created and it is composed by components listed below.

- Robotic arm: it is used for rotating the cube in order that the texture on it is aligned with the VR environment.
- Hand tracking system: it is composed by a camera that is able to detect the hands position in the real world.
- Different textures cube: each surface of the cube is covered by different texture.

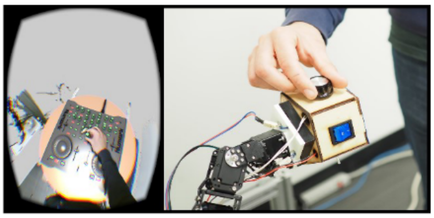


Figure 3.19: System [50].

This technology has two main limitations:

- velocity of the robotic arm in in finger following;
- low spatial resolution.

In work [51] it has been created a device that is able to simulate the shape of a 3D object. This happens thanks to balloons situated on a cylindrical aluminium bar that could rotate and could move up and down (Figure 3.20). A limitation of this technology is that, if a big object is represented, the number of balloons increases.

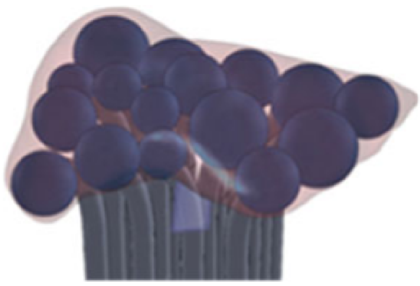


Figure 3.20: Balloons required for creating a virtual lever [51].

In work[52] it is created *HWall*. This system (Figure 3.21) is composed by the components listed beloe.

– Haptic feedback subsystem: it is composed by a cobot that has on the tip a plane with which the user interacts. This cobot is the responsible for the active and passive haptic feedback.

– RGBD sensor: it is used for the hand tracking of the user.

– Headset: it is used for rendering the VR experience.

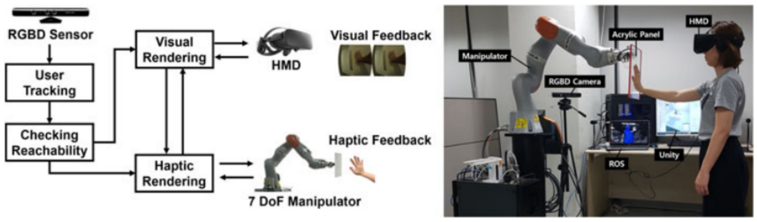


Figure 3.21: The scheme of $HWall$ system [52].

The system renders in a very good way big and rigid surfaces like a wall. The bigger drawback is the limitation in space: if the user turns, the system cannot provide haptic feedback anymore.
In the other encountered systems presented, there was the issue about the user location respect to the haptic device; in order to solve this problem in works [53], [54] are created systems based on the feedback that is provided thanks to a drone (Figure 3.22). With this approach the position of the user does not matter anymore. In system presented in [53] the resistance feedback is provided thanks to the airflow produced by the drone. The solution just described suffers from two issues:

– autonomy of the drone's battery;

– unstable drone's position.

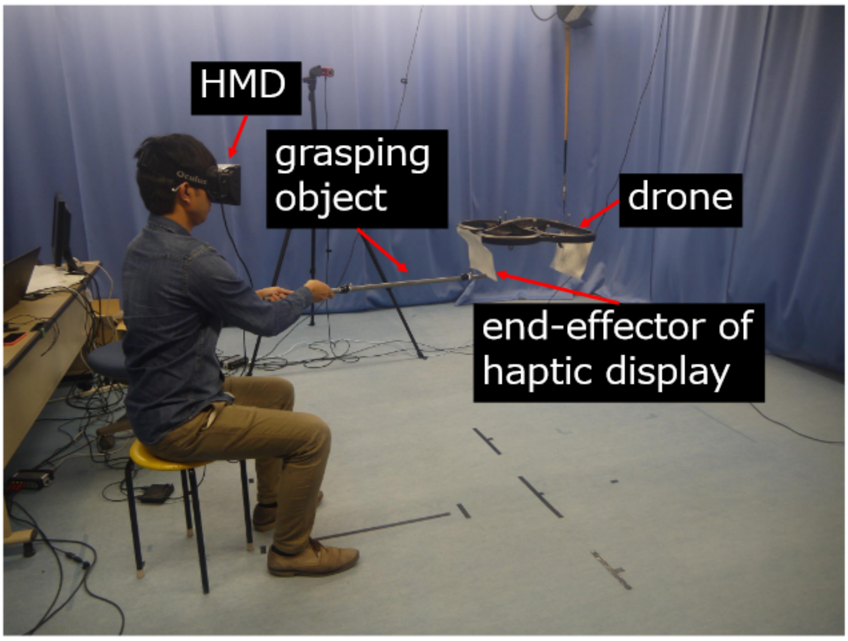


Figure 3.22: Drone system [53]

In work [55] an drone based approach is presented. The drone is used for three main purposes listed below.

- Texture rendering: on the grid around the drone it is attached a texture that is used for VR.
- Props animation: different object could be anchored to drone's grid.
- Passive haptics: the grid around the drone is used for emulating a box or a cube.

This approach, as the other based on drone [53], [54], has issues related to the battery and control. In work [56] it is presented a platform (Figure 3.24), the $Haptic - go - round$, that surrounds the user. On the entire surface of its walls all. The main problem of this device is related to the locomotion: the user cannot explore the virtual environment by using real-walking because he/she has to stay on the platform hence stationary locomotion techniques shall be used to complement the system.

Figure 3.23: On the left the drone is used for texture rendering, in the center the drone is user for animation props and on the right the drone is used for passive haptic purpose [55].

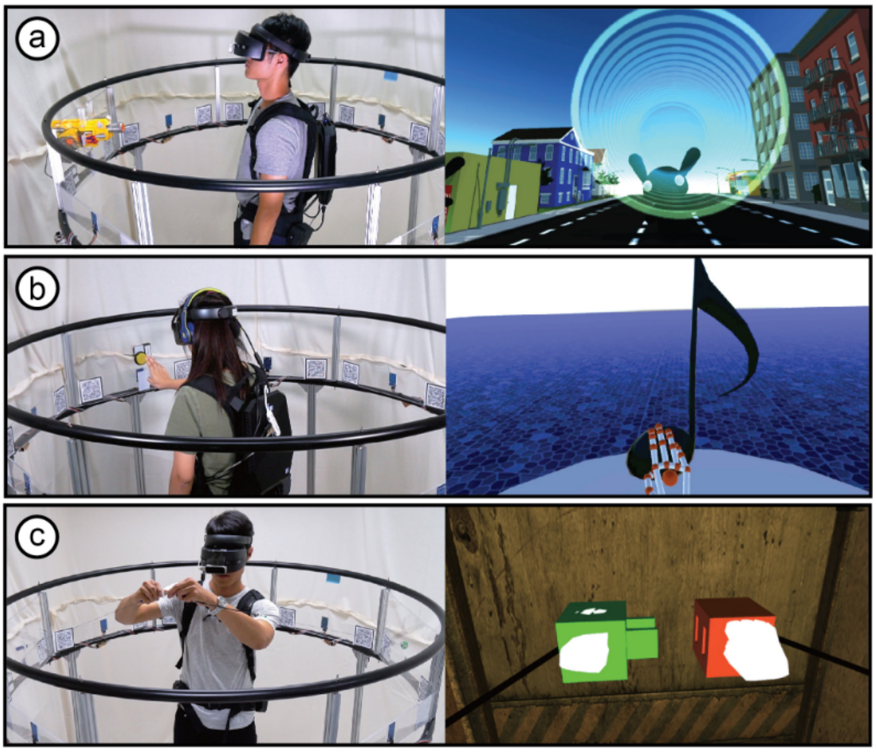


Figure 3.24: $Haptic - go - round$ platform [56].

- Physical props: in work [57] it is possible to transform a square table in table with different shapes (pentagonal and triangular) by using visuo haptic techniques (Figure 3.25) In work [58] *HaptoBend* is created (Figure 3.26).

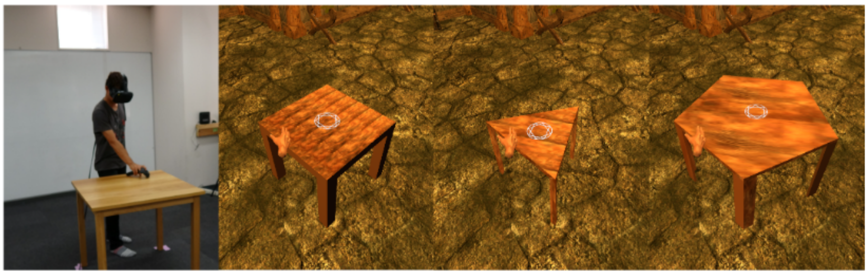


Figure 3.25: Magic table system [57].

It is a device that allows the user to feel an object in VR thanks to passive haptics. In particular this device could approximate four 2D shapes and four 3D shapes. In work [59] it is created a system that is extremely flexible respect to *HaptoBend*. Thanks to versatility of the Lego, it is possible to create passive haptics for unlimited shapes and then track those shapes into VR world by using HTC Vive trackers (Figure 3.27). In this work the user must solve a nuclear power plant emergency and he/she has to interact with passive haptics components made by Lego. However, the main weakness of this study is that the props must be reconfigured by hand. In work [60] it is created a baseball VR experience (Figure 3.28) where the user has to beat the ball with the baseball bat that could be represented by different components that are listed below.

- HTC vive controller.
- Passive haptic weighted prop: the prop has the same weight and shape of a real baseball bat.
- Active haptic weighted prop: the prop has the same weight and shape of a real baseball bat and also it is added some electronics for providingVTF.

The result is that there is performance improvements by using props respect to a controller, but there is not a significant difference between active and passive haptic feedback for this task. In work [61] real hammer, screwdriver and saw are mapped thanks to HTC VIVE trackers and displayed in virtual environment. The result is that, using real tools, the realism is enhanced. In Figure 3.29 is shown the mapping of the real tools to VR environment.

- Mid-air: this type of devices remove all the interfaces and all the sensations are transmitted via ether. In work [62] *UltraHaptics* device is presented (Figure 3.30),. This device is able, by acoustic radiation force, to generate

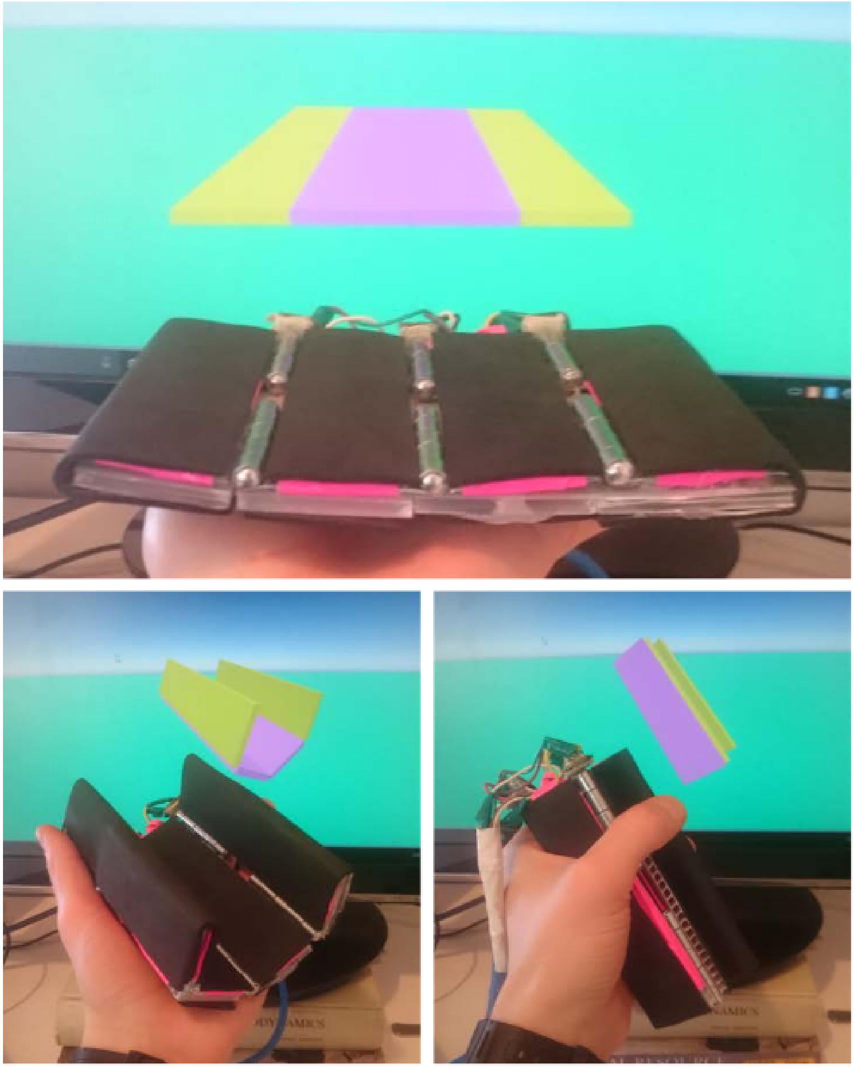


Figure 3.26: *HaptoBend* [58].

haptic sensations on the user's fingers. The device is composed by different components listed below.

- Transducers arrays: they are used for creating focused points in mid-air.
- Display: this is a special kind of display, since it is situated over the transducers. It must be sound transparent.
- Screen projector: it is responsible for rendering the image.
- Hand tracking system: it is used for identifying the position of the hands and the fingers in the space.

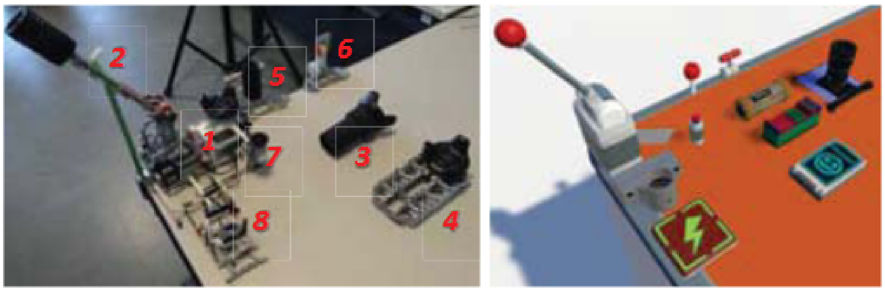


Figure 3.27: A system based on passive haptics Lego [59].

Figure 3.28: Baseball VR [59].

The main issue of this technology is that if the user moves itself he/she cannot feel the haptic feedback anymore. In work [63] transducers arrays are mounted on HMD and used for VR purpose (Figure 3.31). The result is that the testers prefer this technology rather than hand free without haptic feedback, but it has a big limitation that the feedback is not so stronger and could not be perceived by whole hand. In work [64] it has been created a box that has four sides covered by transducers arrays. With this approach a feedback in all the parts of the finger could be provided. The limitation is due to the

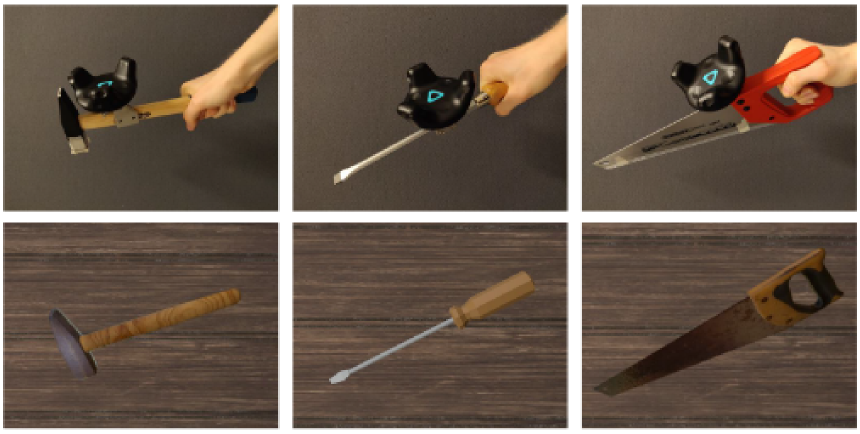


Figure 3.29: Mapping of real world tools to virtual world [61].

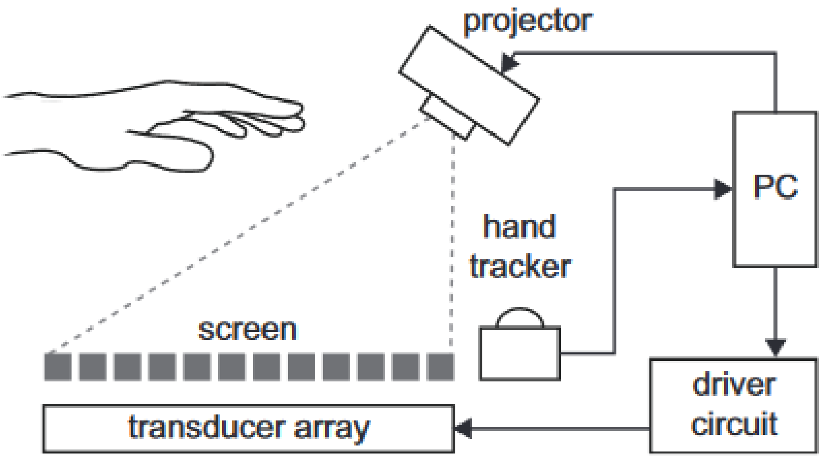


Figure 3.30: *UltraHaptics* device [62].

resolution of ultrasonic distribution. All the mid-air implementations that have been presented suffer from the problem of the relative position respect to the user. If the user moves too much his/her hands this technology does not work anymore. In work [65] it is presented a partial solution to this issue: it is created a mechanical device that allows to enlarge the workspace. In work [66] it is created a device for enhancing the teleport experience: in VR, the locomotion problem could cause cybersickness, issue that is very well discussed in the literature [67]. In particular this device allows the transition between a hot environment to a cold one or vice versa by blowing an airflow.

Figure 3.31: Array of transducers on HMD [63].

3.4 Virtual drilling

The haptic feedback it is fundamental also in drilling and screwdriving operations. For instance, new surgeons it is very important to learn surgical skills, but the training process is very time consuming and it could be dangerous if the approach is based on "learning on patient". To overcome this problem a simulation based on VR can be used. For example in work [68] an haptic device is used to train surgeon in orthopedic drilling simulation (Figure 3.32): in particular a Phantom device is used in a desktop VR experience. The application is judged usable by professional surgeons, but in order to have more realism an HMD could be used.

Figure 3.32: Drilling operation in orthopedic simulation.

An interesting approach is based on work [69], where it is built a pedal haptic device that is able to transmit an haptic feedback based on surgical information to the surgeon. The system is composed by a pedal and a Phantom device and, thanks to them, the user can feel the sensations. In work [70] it is presented a system composed by Phantom device that improves the learning process of the temporal bone anatomy. The results are promising, in fact all the participants improve their examination performances in virtual bone anatomy after having tried the VR simulation. Finally a mid-air haptic feedback could be considered: in work [71] a mockup is created and it is used for simulate a passive haptic feedback during the screwdriver grasp. In order to simulate VTF the Oculus Quest controller vibrates at 150 Hz frequency. The user has to screw four different screws during a VR operations. The user in this situation is helped also by visual information because when the tip collides the screw's head the entire body of the screw become orange. The user has to perform the operations with four different configurations listed below.

- Holding directly a controller.
- Grip only: the user holds an holder for Oculus Quest controller with the same shape of the handle of real screwdriver.
- Grip force: the user holds an holder for Oculus Quest controller with the same shape of the real screwdriver, but less heavy.
- Realistic: the user holds an holder for Oculus Quest controller with the same shape of the real screwdriver, with the same weight.

Figure 3.33: different configurations: on the left the realistic one, on the right the grip only [71].

In this chapter, it is explained that there are a lot of different haptic devices with different characteristics, but, to the best of author's knowledge, a comparison between two different configurations of haptic devices, capable of providing VTF and passive FFB, it is not investigated yet. The chapter that follows moves on to consider the two configurations. These are:

- haptic gloves that can provide VTF and FFB;
- haptic gloves and 3D printed mockup, the first element is used for tracking, while the second one is used for providing passive FFB and VTF.

In order to evaluate these configurations a use case, based on electric screwdriver, is selected.

Chapter 4

Design and Realization

The section below describes how the VR application is designed and then, how it is implemented, focusing on the procedure creation and haptic management.

4.1 Application design

The VR application may be divided into several groups that are listed below.

- tutorial: in this part the user has the opportunity to learn how to interact with objects: as it can be seen in Figure 4.1 there are three cubes with different dimensions that have to be grabbed and put in a certain place. In this part also the user understands how the information are provided in virtual environment.

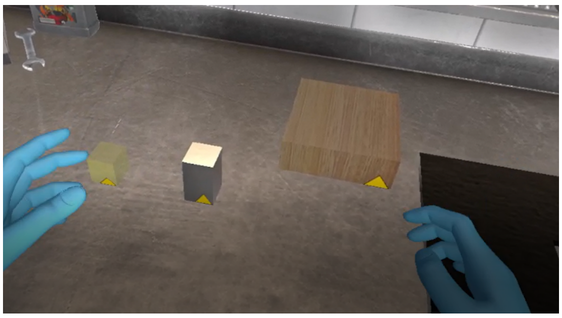
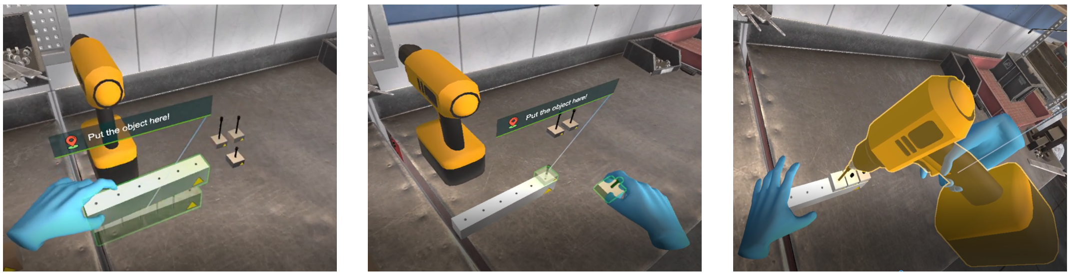


Figure 4.1: Tutorial objects.

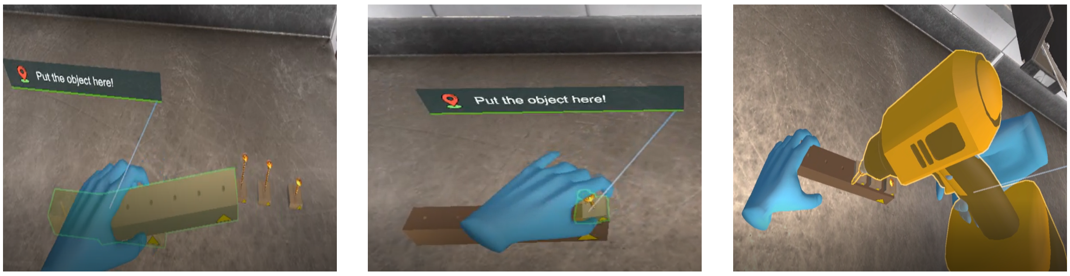
- Aluminium screwing: after the tutorial the user has to grab the bar and put it in the correct position and then has to grab one gusset at time, put it in the right place and, finally, screw the corresponding screw (Figure 4.2). The process described has to be repeated by the user three times.



(a) Bar manipulation. (b) Gusset manipulation. (c) Screwing.

Figure 4.2: Aluminium screwing.

- Wood screwing: the user in this second part has to perform the same operations that he did before in aluminium. In Figure 4.3 the bar manipulation, gussets manipulation and screwing can be seen.



(a) Bar manipulation. (b) Gusset manipulation. (c) Screwing.

Figure 4.3: Wood screwing.

Since in this work two different configurations are considered, each user has to try the procedure just described two times.

4.2 Application creation

In order to create a procedure a tool powered by TXT Group has been used: Pacelab WEAVR [72]. The approach of WEAVR is coding-free: it makes available to the user a visual interface composed by different nodes and each node is a step of the procedure. Each node is separable in three parts described below.

- Enter actions: here there are all the actions that are performed when the procedure enters in the current node. A typical enter action is the text-to-speech: thanks to AWS services a speech synthesis function explains to the user what he/she is going to do in the current step.

- Exit conditions: in this node's field there are all the conditions that are exploited in order to exit from the current node; for example it could be a value of a variable or the position of an object.
- Exit actions: these are all the actions that are called when at least one of the exit condition is exploited; in the procedure created for this work in the exit actions there is a function that registers how long did the user take to perform a step of the procedure.

The logic behind the procedure could be divided in three different nodes.

- *Grab node*: this node is used for the grabbing. In the enter section of this type of node there is a text-to-speech synthesis that allows the virtual assistant to drive the user in this procedure step; there is another function that is used for the outline of the object that must be grabbed in the current step of the procedure. The exit conditions are triggered thanks to SenseGlove SDK or ManusVR SDK, which are able to detect if a certain object is picked up or not; the first detection is based on the colliders position and the second one is based on gesture recognition.

Figure 4.4: *Grab node.*

- *Move node*: this node is used for moving the object that the user holds in the hand to the correct position. Like with previous node also in this case in the enter actions there is a text-to-speech and a function that enables the billboard and outlines. The difference with respect to the *Grab node* is inside the exit conditions and the exit functions. The conditions are two:

- the user must open the hand and so the piece will be released;
- the piece must be placed in the correct place; this control is made by comparing the component Transform of the object that the user has in his/her hand and the collider of the position where the object should be placed.

If both the conditions are satisfied the exit actions are called:

- an animation puts the the object exactly in the correct position; this action is performed since the user, often, does not put precisely the object in the correct position;
- the material of the "ghost" object becomes the correct one;
- the object that was grabbed by the user is disabled or in the case of ManusVR SDK, the component MeshRenderer of the previous grabbed object is disabled instead of the object itself; this choice is due to the problem that if an object that is grabbed is disabled, the releasing function is not invoked and the system crashes.

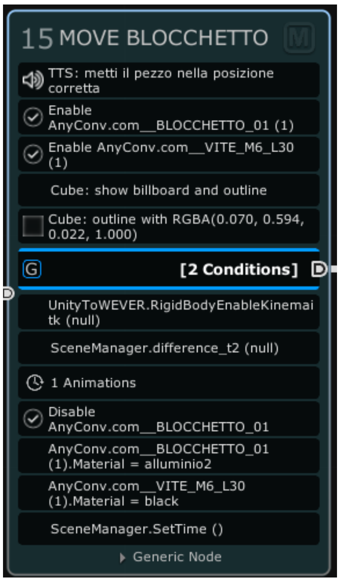


Figure 4.5: *Move node.*

- *Drilling node*: this node is related to the screw and the drill. When the user arrives in this part of procedure he/she must screw the correct screw. Also in this node there is a text-to-speech function powered by AWS and a billboard that indicates that the user has to interact with the drill. The exit condition is related to the fact that the correct screw gets to the end of the stroke.

Figure 4.6: Drilling node.

4.3 SenseGlove

The experience could be delivered by using SenseGlove haptic gloves. They are able to represent FFB and vibrational feedback to the end-user. Thanks to their SDK it is possible to control every motor inside the fingertip and also the quantity of FFB for each finger. It is important to underline that these motors can only block the finger: it is not possible to pull the finger but only to block them in a certain position. In order to perform the manipulation task, each GameObject present into the scene must have four componets.

- *Collider*: this is the base class from which the other classes (box colliders, sphere colliders, etc...) inherit their properties; this component allows the GameObject to have a collision area and the related collision functions.
- *RigidBody*: this component is responsible for the physics of the GameObject; in particular, thanks to this component, an object could have a certain mass, it could be sensitive to the gravity or it could rotate only on a certain axis.
- *Grabbable script*: this is useful for the grab detection and the release recognition and also for the attachment during the grabbing; this last feature allows the object to be snapped in a certain position after that the grab is detected. In Figure 4.7 it can be seen how a virtual hand is interacting with a simple orange sphere; in particular the red spheres are the colliders related to each finger and the other object that has a cube shape is the collider related to the hand's palm.

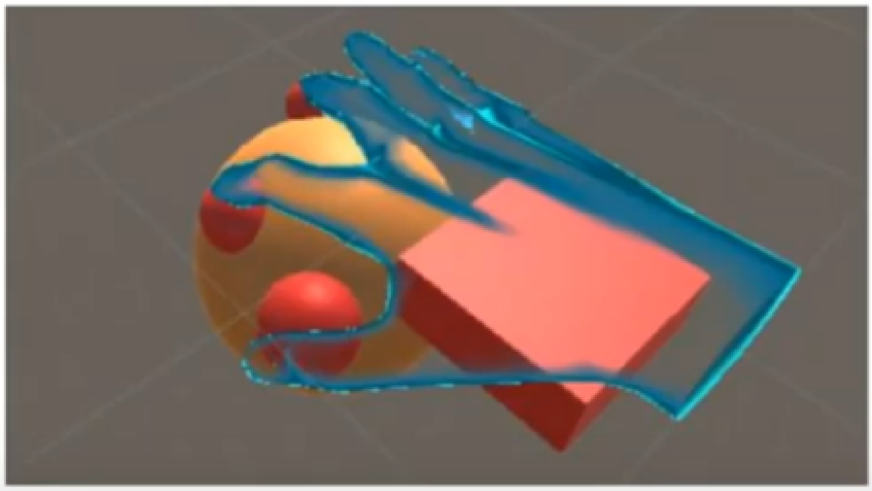


Figure 4.7: Hand that is interacting with an orange sphere.

- *Material script*: this component allows the user to feel the shape of an object thanks to FFB. In particular the force computation is based on the distance of each finger inside the collider; the amount of force applied on the finger is based on the relative position between the collider and the finger. In Figure 4.8 it can be seen a simple object that is interacting with an hand and in Figure 4.9 there is the force-curve response related to that object. In Figure 4.9 a rigid object is presented, it has a force-feedback that is always at maximum value, independently of the finger displacement. When a finger interacts with that object it is calculated the force displacement between the entry point of the finger collider and the current position of the finger; for each update it is computed the correct level of force-feedback based on the force-response curve and the finger displacement. The final value it is sent to gloves.

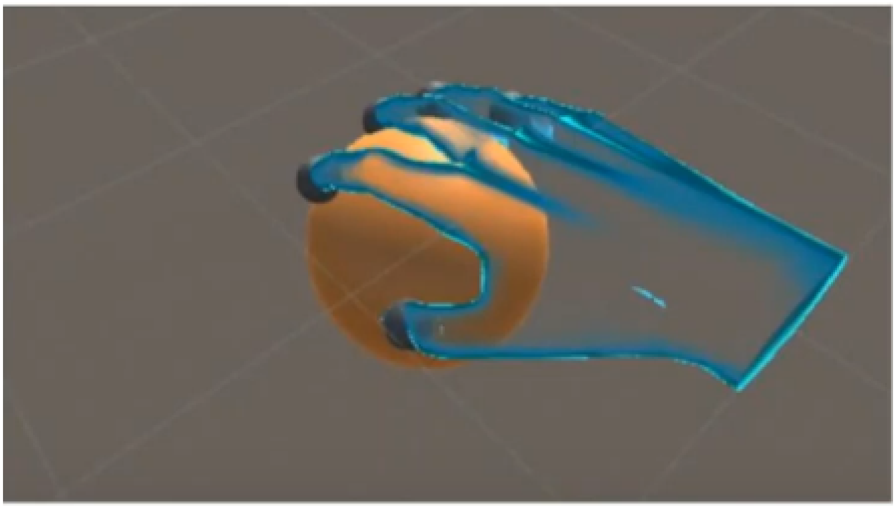


Figure 4.8: Hand interacts with a ball.

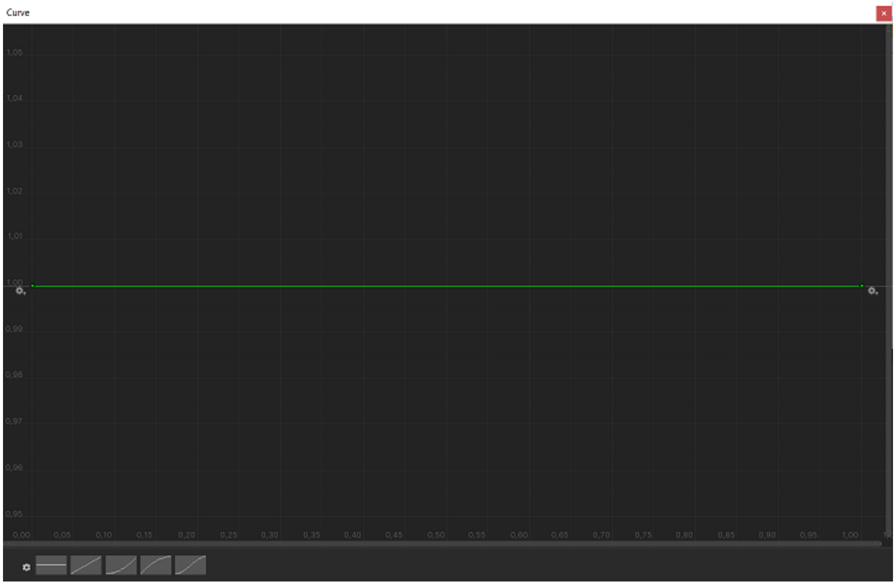


Figure 4.9: Force-feedback curve of a rigid object.

4.4 VTF waveform implementation

Thanks to an Arduino UNO and an ADXL345 module put on the handle of screwdriver, it was possible to retrieve the information for the acceleration and consequently, by using Discrete Fourier Transform (DFT), the vibration of a real screwdriver. The communication between the microcontroller and the module was created by $I2C$ protocol by using the $Wire.h$ library. The Arduino was used as master and the ADXL345 as a slave with unique address $0X53$. In this configuration there are two lines:

- $SCLK$: since $I2C$ is a synchronous protocol it must have a clock signal;
- $SDATA$: in this bus all the data are transmitted.

In order to enable the measuring function, it is necessary to write 8(dec) in the controlling power register (Figure 4.10).

Register 0x2D—POWER_CTL (Read/Write)

D7	D6	D5	D4	D3	D2	D1	D0
0	0	Link	AUTO_SLEEP	Measure	Sleep	Wakeup	

Figure 4.10: Power control register, datasheet ADXL345.

In order to correctly read the data two registers are used (Figure 4.11), this because the datum is on 16 bit, so the algorithm has to read 8 bits each time and then combine the values by shift operation. The output data is twos complement with DATA×0 as the last significant byte and DATA×1 as the most significant byte.

DATAx1 REGISTER

D7	D6	D5	D4	D3	D2	D1	D0
D7	D6	D5	D4	D3	D2	D1	D0

DATAx0 REGISTER

D7	D6	D5	D4	D3	D2	D1	D0
D7	D6	D5	D4	D3	D2	D1	0

Figure 4.11: Data register.

In ordered to obtain the correct acceleration's values, the Single-Axis (SA321) process is used as in [73] and in [74]. With this approach an axis is fixed and the acceleration calculation is based on its positional variations. At the end of the acquisition process the series values are obtained and then it is applied the DFT, thus obtaining the frequency. This process was repeated in four different conditions:

- mid-air;
- screwing in the wood;
- screwing in the aluminium;
- at the end of the stroke.

In Figure 4.12, Figure 4.13 Figure 4.14, Figure 4.15 the different behaviours can be seen. In the wood the behavior is influenced by more waveforms with respect to the aluminium: this is due to the fact that in the wood the thread is not present. On the contrary, the aluminium hole must be threaded otherwise the screw is not able to screw the material. The main difference between aluminium and mid-air is related to the intensity of the signal; moreover, in the aluminium there is a bigger noise due to the contact of the tip with the material. When the tip reached the end-of-stroke the noise became high, but it can be seen a peak generated by 150 Hz sinusoid. As the Pacinian Corpuscles are sensible to high frequencies in the range 40-400 Hz, the signal is evaluated in this range, by using a sample frequency of 800 Hz as in example in [75]. By considering in detail the different sensations it can be seen that in every condition there is a peak in correspondences of 150 Hz sinusoid. It can be noticed that in the mid-air condition the noise component has an amplitude that is lower than in the other conditions, especially if it is considered the end-of-stroke condition. In order to request data in a correct way

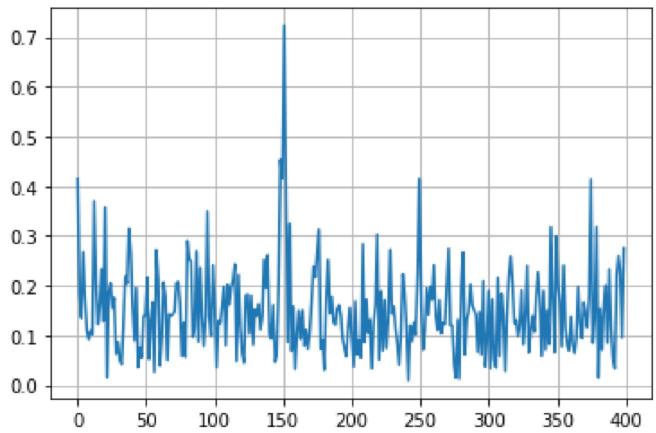


Figure 4.12: Aluminium vibration.

the TIMER1 of Arduino UNO is used. In particular the registers that are used are the following:

- $TCNT1$: in this register it is stored the current value of the counter;
- $OCR1A$: it is stored the number of ticks that, when reached by TCNT1, fires an interrupt;
- $TIMSK$: it is used for enabling the output compare interrupt;
- $TCCR1B$: it is used for setting the correct prescaler.

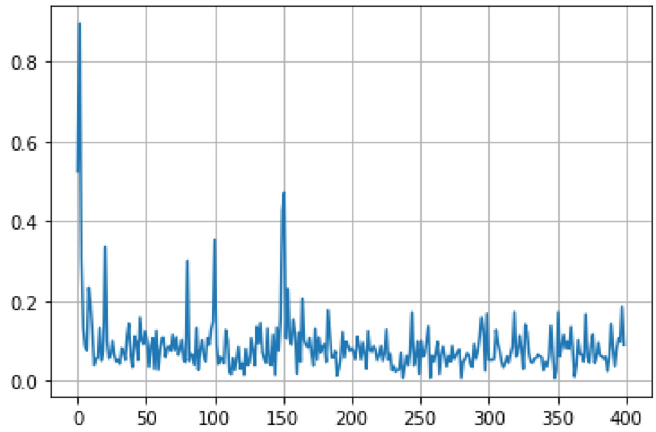


Figure 4.13: Mid-air vibration.

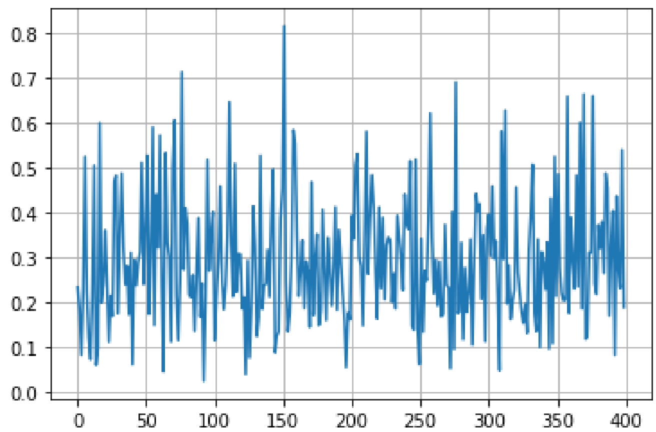


Figure 4.14: End-of-stroke vibration.

In the register $OCR1A$ it is set a value equals to 20000, in the $TCCR1B$ only the bit related to $CS10$ is set to 1, this means that the prescaler is equal to one. In the register $TIMSK$ the bit $OCIE1A$ is set to 1 and that causes the enabling of interrupt related to output compare.

Bit	7	6	5	4	3	2	1	0	
(0x81)	ICNC1	ICES1	–	WGM13	WGM12	CS12	CS11	CS10	TCCR1B
Read/Write	R/W	R/W	R	R/W	R/W	R/W	R/W	R/W	
Initial Value	0	0	0	0	0	0	0	0	

Figure 4.16: TCCR1B register.

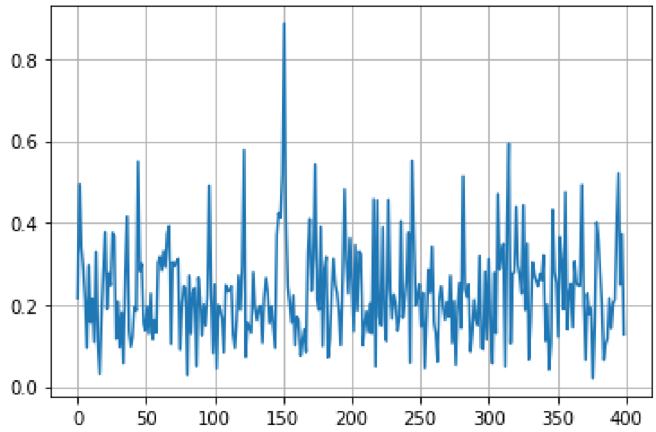


Figure 4.15: Wood vibration.

Bit	7	6	5	4	3	2	1	0	
(0x85)	TCNT1[15:8]								TCNT1H
(0x84)	TCNT1[7:0]								TCNT1L
Read/Write	R/W	R/W	R/W	R/W	R/W	R/W	R/W	R/W	
Initial Value	0	0	0	0	0	0	0	0	

Figure 4.17: TCNT1 register.

Bit	7	6	5	4	3	2	1	0	
(0x89)	OCR1A[15:8]								OCR1AH
(0x88)	OCR1A[7:0]								OCR1AL
Read/Write	R/W	R/W	R/W	R/W	R/W	R/W	R/W	R/W	
Initial Value	0	0	0	0	0	0	0	0	

Figure 4.18: OCR1A register.

Bit	7	6	5	4	3	2	1	0	
(0x6F)	–	–	ICIE1	–	–	OCIE1B	OCIE1A	TOIE1	TIMSK1
Read/Write	R	R	R/W	R	R	R/W	R/W	R/W	
Initial Value	0	0	0	0	0	0	0	0	

Figure 4.19: TIMSK1 register.

4.5 Mockup and ManusVR

In this section it is described how the configuration, composed by the mockup and the ManusVR gloves, works. The system is composed by two main components:

- ManusVR gloves: they are able to provide haptic feedback and handle the tracking for the hands of the user. During the manipulation task these gloves are used for notifying the user when he/she picks up or releases a certain object. The notification is a vibration with maximum amplitude on every fingertip. It is important that the calibration is done at least one time per day.
- Mockup: it is used for providing passive FFB, it has a shape of the handle of a real screwdriver.

Figure 4.20: Configuration composed by ManusVR gloves and mockup.

4.6 Waveform rendering

In this section it is explored how are designed different haptic sensations. The goal of this work was to render different kinds of sensations. The part of the screwdriver that is responsible for haptic sensations is the tip. As it can be seen in Figure 4.28 the tip has a collider zone with capsule shape; this zone is responsible for the different sensations that are rendered on the hardware. In Section 4.4 it was shown that in all the conditions (mid-air, screwing in the steel, screwing in wood or at the end-of–stroke) the waveforms that causes the major peak in the frequency domain is a sinusoid at 150 Hz; so, this frequency has been used in the VR experience. The different sensations that are rendered are those listed below.

- Material independent: the sensation that are not dependant on material can be listed below.
  - Mid-air screwing: in this condition the tip is in contact only with the air, not with some solid pieces; to represent this type of sensation a sinusoid waveform is chosen with an amplitude that depends on how much the trigger of the drill is pressed (Figure 4.21).

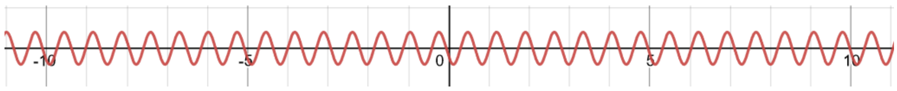


Figure 4.21: Mid-air waveform.

  - Collision between the tip and the screw: in this situation the tip is colliding with the screw head, so there is a vibration that is rendered only for 0.05 s.

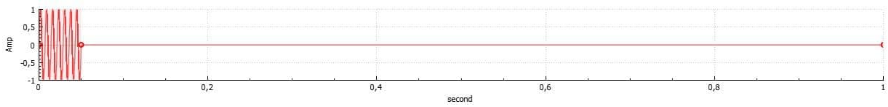


Figure 4.22: Waveform rendered when the tip collides with screw.

  - Collision between the tip and an object that is not a screw: in this situation the tip is colliding with an object with which shouldn't have interacted. The waveform is a sinusoid at 150 Hz (Figure 4.23).

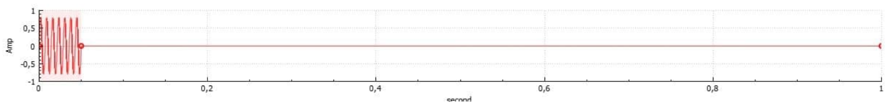


Figure 4.23: Waveform rendered when the tip collides with object that is not a screw.

- Material dependent: the senstations perceived that are dependent on material could be listed as follows.
  - The screws arrives at the stroke end in wood: in this condition the screw, related to the wood, has been screwed. As can be seen in Figure 4.24 the

sinusoid is at 150 Hz but there are also some points were the amplitude is equal to 0 and so the user feel a strong discontinuous sensation passing from an amplitude equals to one to an amplitude equals to 0.

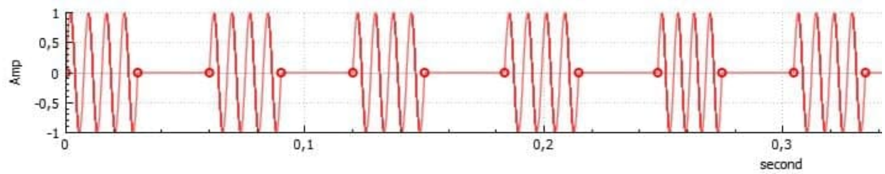


Figure 4.24: Waveform rendered when the screw arrives at the stroke end in the wood.

– When the screws arrives at the stroke end in aluminium: this sensation is similar to the one that is discussed before. The waveform can be found in Figure 4.25.

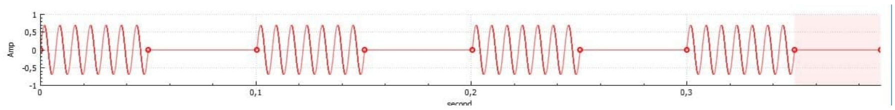


Figure 4.25: Waveform rendered when the screws arrives at the stroke end in the aluminium.

– Screwing in the aluminium: this situation is related to the screw process by using aluminium material; this behavior is due to the thread that does not cause the discontinuities in the screwing process (in fact there aren't the waveforms parts where the amplitude is equal to zero) (Figure 4.26).

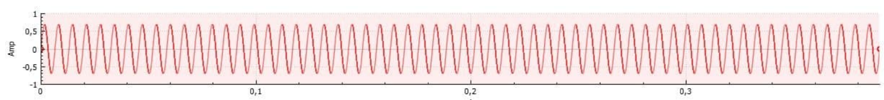


Figure 4.26: Waveform rendered when screwing in the aluminium.

– Screwing in the wood: in this situation the user is screwing the screw inside the wood; the sensations are different respect to those related to aluminium because in this case the thread is absent (Figure 4.27).

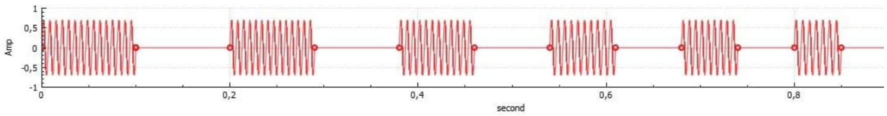


Figure 4.27: Waveform rendered in screwing in the wood.

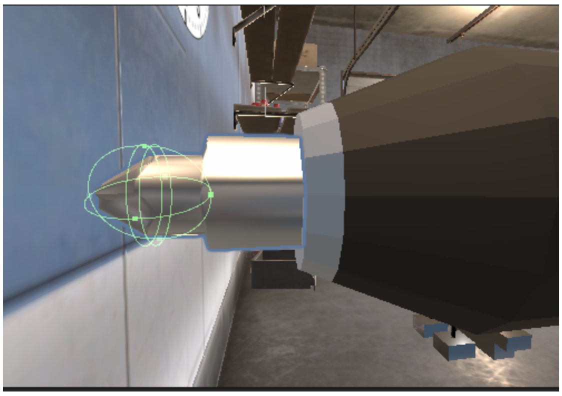


Figure 4.28: Collider of the tip.

4.7 Aluminium

In order to create the aluminium gussets and bar for the real world experiments, a milling machine was necessary. For this purpose the one in Assocam Scuola Camerana [76] is used. Before starting the milling operations in order to obtain the necessary pieces it is important to setup correctly the machine. In this case a DMG 635 Ecoline milling machine is used. In order to perform the setup of CNC machine it is necessary to have different instruments that could be seen in Figure 4.29.

Figure 4.29: Instrument for the setup of the milling machine.

Before putting the piece inside the milling machine it is important to deburr the raw block, and also the user must execute all the commands that are needed for the correct alignment of the equipment respect to the machine's axes. In order to give to the machine the correct commands in this case a SIEMENS 840 SD is used. In order to have the correct piece at the end of the mechanical processing, two different programs have been used: the first one is used for the elaboration of entire surface except for the bottom of the block and the other one is developed for drilling only the bottom, in order to complete the piece. The same approach is used for the bar, and in Figure 4.30 the aluminium assembly could be seen.

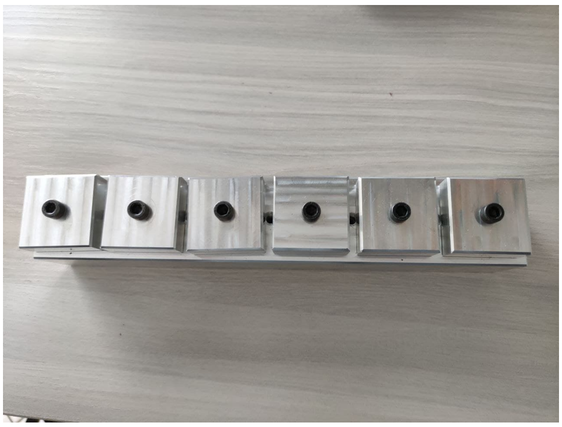


Figure 4.30: The assembly of the aluminium structure.

4.8 Wood

In order to create the gussets and bars for the real world experience, starting from a fir's wood bar, by using a band saw, are created two different typologies of objects:

- gussets are produced with dimensions 40×40×20 mm;
- bars are produced with dimensions 60×60×150 mm.

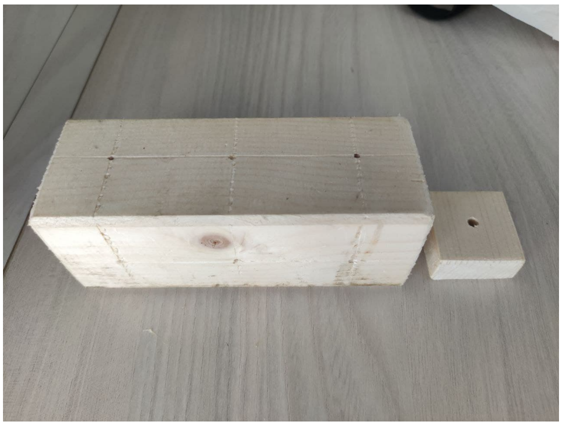


Figure 4.31: Gusset and bar.

These object listed above are not threaded, in fact the Parker screw is able to deform the wood and consequently to fix the gusset to the bar.

4.9 VR simulation environment

In this section the VR scene is described. The user is in a workshop, with an interaction area of 2.1×0.95×1.35 m, and in front of him/her, at the height of 0.9 m, there is a workstation where he/she will perform all operations during the experience. The whole experience is divided in three parts:

- tutorial;
- aluminium screwing;
- wood screwing.

The tutorial allows the user to become familiar with the the configuration that he/she is using. In this part of the experience he/she has to grab three different pieces and put them in the correct position. The task is subdivided in two parts:

- grabbing: the user has to pick up the correct piece for each step; the grabbing action is detected thanks to SenseGlove SDK or Manus SDK;
- moving: after the grabbing operation the user has to put the object that holds in his/her hand in the correct position; during this step he/she has to take into account the correct position of the object by using the little triangle.

In Figure 4.32 the three tutorial objects can be seen; starting from the left the three dimensions are:

- 0.045×0.061×0.047 m;
- 0.050×0.104×0.050 m;
- 0.210×0.080×0.220 m.

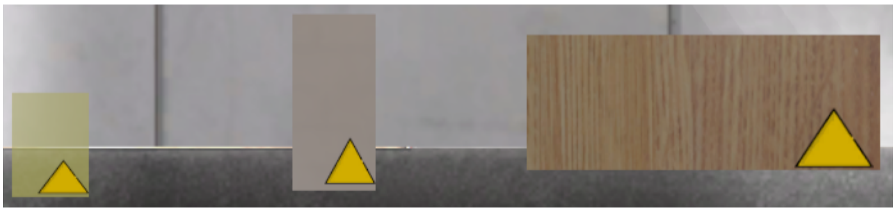


Figure 4.32: Tutorial objects.

After the familiarization phase the user starts with the screwing task related to aluminium and wood, the goal is to screw three different screws with different lengths in an aluminium bar and in a wood bar. To perform this task the user has to perform three different actions, listed below.

- Grabbing: this action is similar to the one that the user has performed in tutorial; he/she has to pick up a block (0.04×0.02×0.04 m) or a bar (0.26×0.05×0.04 m).
- Moving: after the grabbing, as happened in tutorial, the user has to move the object and release it in correspondence of the correct position.
- Screwing: the user has to use the electrical screwdriver to screw different screws.

In the application related to the configuration with ManusVR and mockup, at the beginning of the tutorial a table calibration is needed. The system automatically translate the virtual environment respect to the real world position of the mockup; this action can result in perfect match between virtual table and the real one.

4.10 Screwdriver

The drill is the instrument that is used for the screwing operation. It is represented in the virtual scene in a different ways depending on which system is used. If the SenseGlove is considered, the shape of the drill is rendered thanks to force-feedback offered by the hardware and the haptic feedback is provided by ERM motors inside the fingertips. If the system is composed by the ManusVR gloves and the mockup, the former ManusVR is used for hand and finger tracking inside the VR space and the latter is used for a passive FFB and for generating haptic feedback thanks to a vibration motor inside the controller. Both systems try to represent in the best way possible not the whole structure of the drilling device, but the two part below.

- Handle: this part is where the user grasp the drill. It has a dimension of 0.03×0.13×0.03 m. In the case of SenseGlove it is used a material with force-displacement curve as the one in Figure 4.9, because in real life that part of the drill is made by a strong material, so it cannot be squeezed. The mockup, thanks to its natural shape, offers a passive FFB.

Figure 4.33: Drill.

- Trigger: it is the button that it responsible for the tip motion. In the case of the physical mockup this behaviour is reproduced thanks to the button of the controller, whereas if the system is composed by the SenseGlove the force-displacement curve (Figure 4.34) is sampled. This curve represents a behavior in which the FFB increases its value proportionally to the distance between the starting point of the collider and the position of the finger; in this situation the Max distance value is equal to 0.029 m, because it corresponds to the value when the trigger is completely pressed.

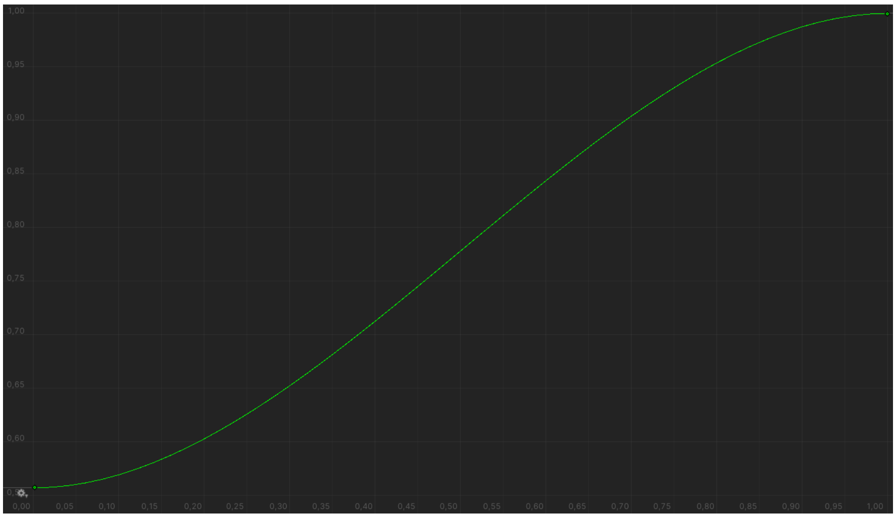


Figure 4.34: Force-displacement curve of the trigger button.

Chapter 5

Experiment Design

Here it is described the design of the experiments. In order to evaluate the users' performances both subjective 5.2 and objective metrics 5.1 are used. In particular the objective metrics are collected automatically; in contrary, the subjective are collected by using questionnaires.

5.1 Objective metrics

The metrics that are used for this purpose are reported below.

- How much time the user takes in order to perform a specific step of the procedure.
- The precision in the screwing process: each screw has got a correct screwing point. As it can be seen in Figure 5.1 it is a point that is in the center of the screw's head. As a metric, it is taken the average point that has been collided by the tip in the screwing process and then a difference is calculated.

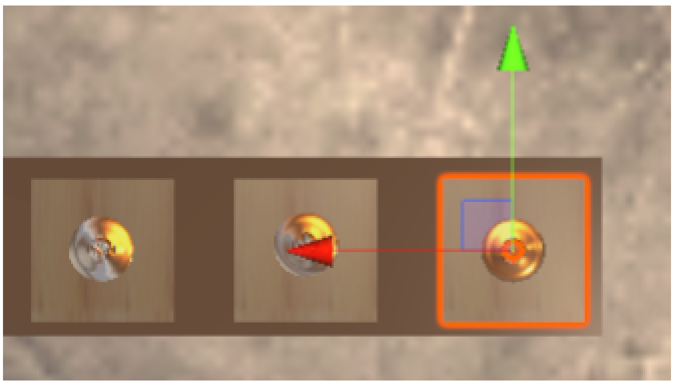


Figure 5.1: On the rightmost screw the correct screwing point could be seen.

- Maximum and minimum angle of the tip with respect to the current screw: during the screwing operations the user should maintain the tip in line with the center of the screw's head (Figure 5.2).

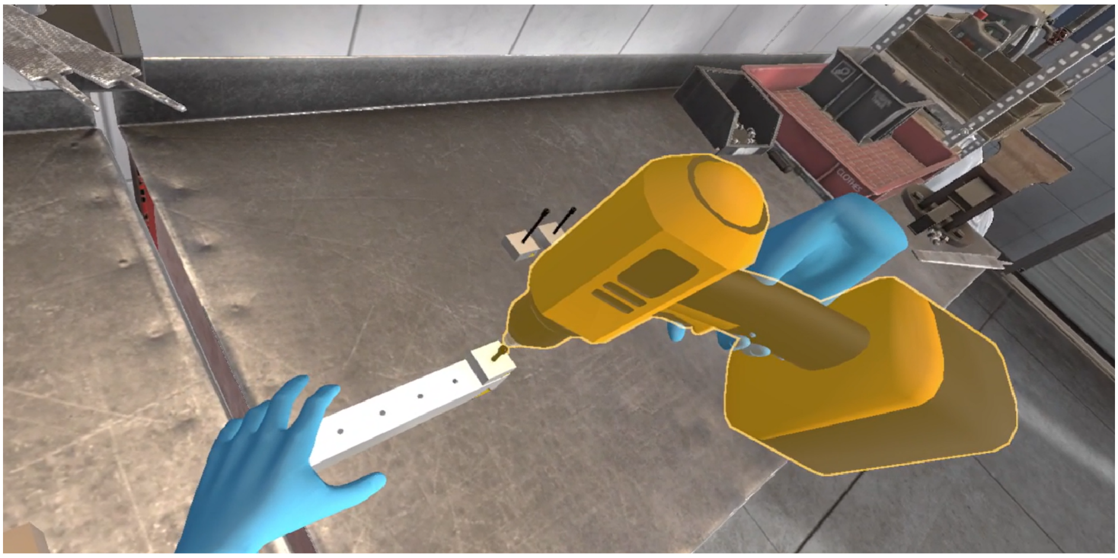


Figure 5.2: Screwing operation, the user has to align the screwdriver tip with the screw's head.

- Correct position and rotation of the current object with respect to the ghost object: in the procedure the user has to manipulate different objects, like the tutorial cubes, the bars and the blocks. Each of these objects has got a complementary ghost object (Figure 5.3) made by the same material but with an higher transparency. The user should match the position and rotation of the object that holds in his/her hand with the position and orientation of the corresponding ghost object.

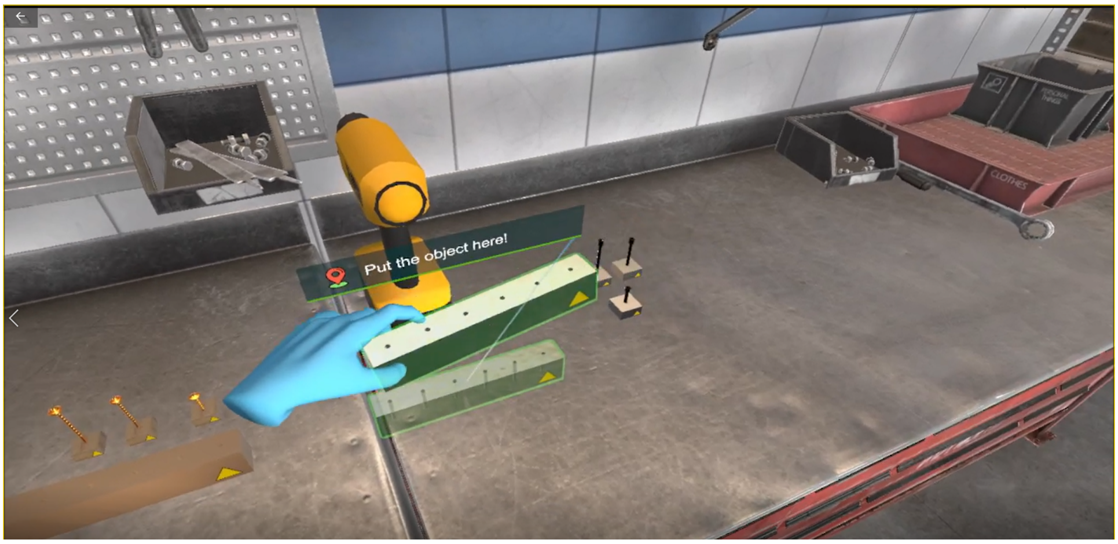


Figure 5.3: The user should be able to put the bar that has in his/her hand in the correct position with the correct orientation.

- Time that the user passes at the end of the stroke for each screw: when the user reaches the end of the stroke, he/she must stop screwing because otherwise the tip will be ruined.
- Number of times the user picks up the electric screwdriver.
- Number of slips.
- Time elapsed at screwing in mid-air.

5.2 Subjective metrics

In order to evaluate the users' performance from a subjective view points, questionnaires (Appendix A for more details) were also used besides the objective metrics, as reported below.

- Pre-experience questionnaire: it was used for the generalities of the user that performed the task.
- Post usage of real world experience: it was used for understanding which were the different sensations perceived in real world by the user.
- The System Usability Scale (SUS) [77]: it was created by John Brooke in 1986 and it was used for measuring the usability of the system.

- SIM-TLX [78]: it was created starting from NASA-TLX, and it was used to evaluate:
  - mental demands;
  - physical demands;
  - temporal demands;
  - frustration;
  - task complexity;
  - situational stress;
  - distraction;
  - perceptual strain;
  - task control;
  - presence.
- VRUSE [79]: also this questionnaire was used for evaluating the usability of the system.
- User Experience Questionnaire (UEQ) [80]: it was used for measuring user experience aspects like originality and stimulation.
- Custom questionnaire: it was used for comparing the two systems.

5.3 Tests organization

In order to perform the tests, Leonardo made available the equipment used in the experiments and contributed to the user with 15 people. Each user was assigned an integer ID, from 1 to 15; the environment for the test is the Virtual Lab situated in Leonardo Aircraft [81] and the hardware used was HTC Vive ecosystem that is composed by the headset, two controllers, two trackers and two base stations. The material that composes the real world experience could be seen Figure 5.4.

- electric screwdriver and battery;
- wood bar;
- aluminium bar;
- aluminium blocks;
- wood blocks;
- screws for aluminium;

- screws for wood.

Figure 5.4: Physical material used in the experiments.

Each user had to participate to three experiences, described below.

- Real world experience: the user has got in front of him/her a table with above the same configuration that he will try in VR (Figure 5.5). He/She should put the blocks in the correct position and then screw three screws with different lengths in the wood and three screws with different lengths in the aluminium; during this process he/she must pay attention to the different sensations that he/she is feeling, focusing on:

  - the haptic sensation in mid-air;
  - when the tip enters in contact with the screw;
  - when the tip is removed from the screw, due to a wrong angle between the the tip and the screw;
  - the difference in screwing process between the wood and aluminium;
  - the perception of the end of the stroke.

Figure 5.5: Real world experience, the user screwing in the wood.

- ManusVR gloves and mockup: in this scenario the user uses the system that is composed by the ManusVR gloves, that are tracked thanks to HTC Vive trackers, and the mockup, with inside the controller, representing the electric screwdriver (Figure 5.6). He/She has to perform all the tasks that he/she experienced in real world.

Figure 5.6: The user is screwing using ManusVR and mockup.

- SenseGlove: in this scenario the system is composed by SenseGlove with trackers mounted above. Also in this case the user has to replicate all the actions that he/she performed in real world (Figure 5.7).

Figure 5.7: The user is screwing using SenseGlove.

For all the testers the first experience to be tried was the one related to real world, while the order of the second one and third one depended on the ID of the user: the odd IDs tried the SenseGlove experience as second, whereas the even IDs the one based on ManusVR and the mockup.

Chapter 6

Results

In this chapter the results of the tests are presented. As said, each user was assigned an ID (from 1 to 15). The first questionnaire section was used to collect general information on the users: all the user were male with an average age of 36 years. With D'Agostino-Pearson test the normality is checked and then data analysis has been performed using two-tailed paired t-tests. It was asked to the users also about their experience with VR technology; the graph in Figure 6.1 represents this information. There are three people that uses this technology everyday (IDs: 1,2,8) but the mean is less than three, meaning that on average the users use VR one time per month.

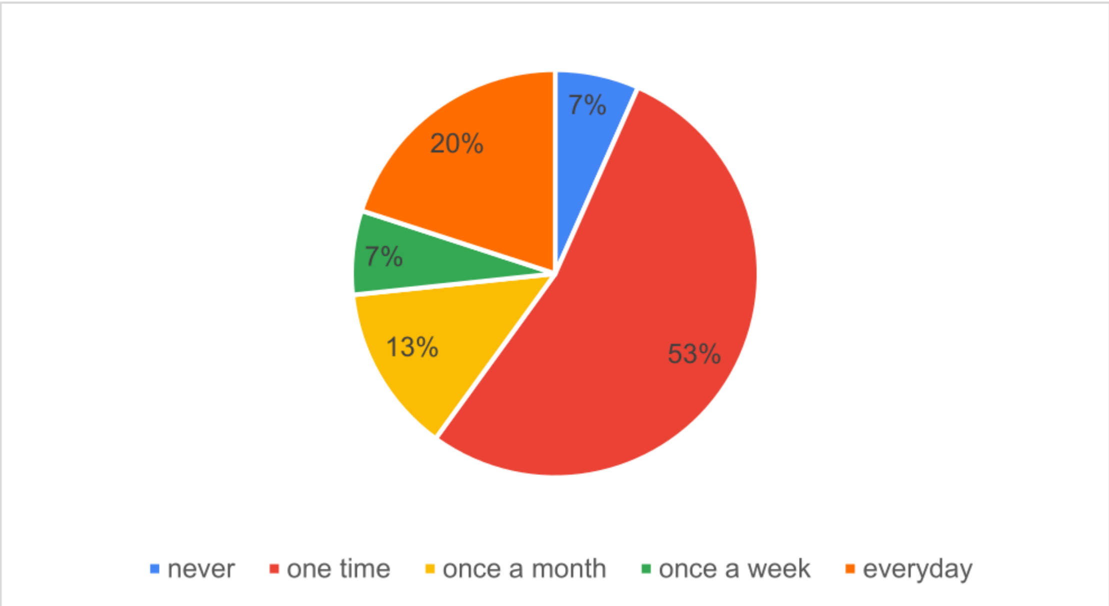


Figure 6.1: The representation of how much a certain person uses VR.

The graph in Figure 6.2 displays the experience related to the screwdriver's usage. As it can be seen the mean is three, meaning that the users use the screwdriver sometimes.

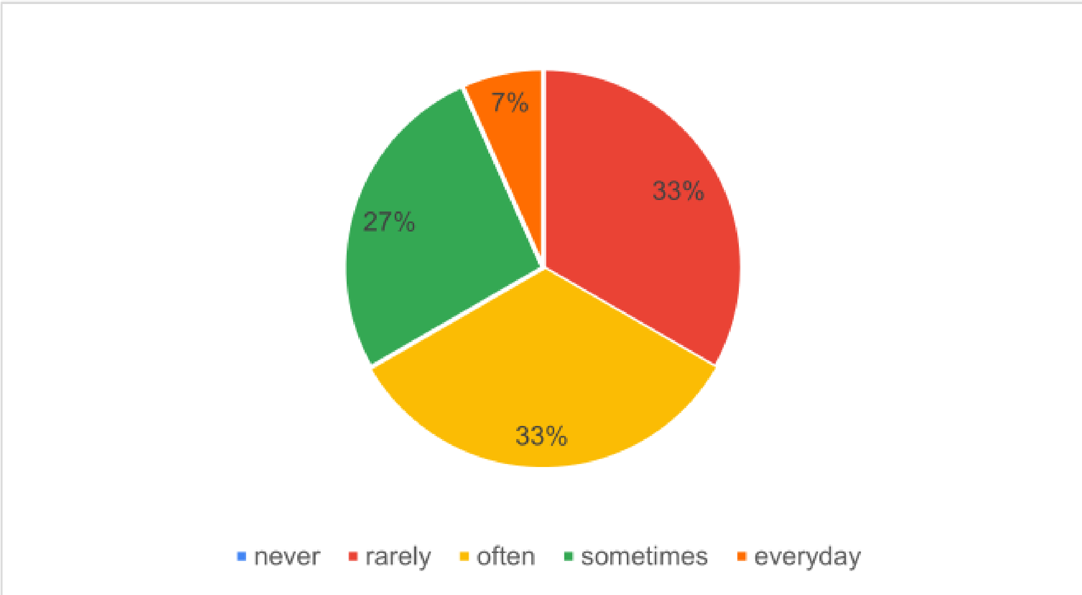


Figure 6.2: The representation of how much a certain person uses screwdriver.

Here are discussed the results after the real world experience A.2. In Figure 6.3 on the horizontal axis it is displayed the number of the questions asked and on the vertical axis a value from 1 to 5, where 1 is strongly disagree and 5 is strongly agree. It can be noticed that in general each user perceived different sensations while he/she was screwing in wood or in aluminium and also that each user recognized the moment when the tip collided with the screw's head and also when it arrived at the end of the stroke. It can be noticed that the only sensation that was only partially felt was the one related to a possibly different haptic feedback in correspondence of different screw's lengths; this outcome was due to the fact that in the aluminium there is already the thread, whereas in the wood the user perceives an increased torque while screwing with respect to different vibration's perception.

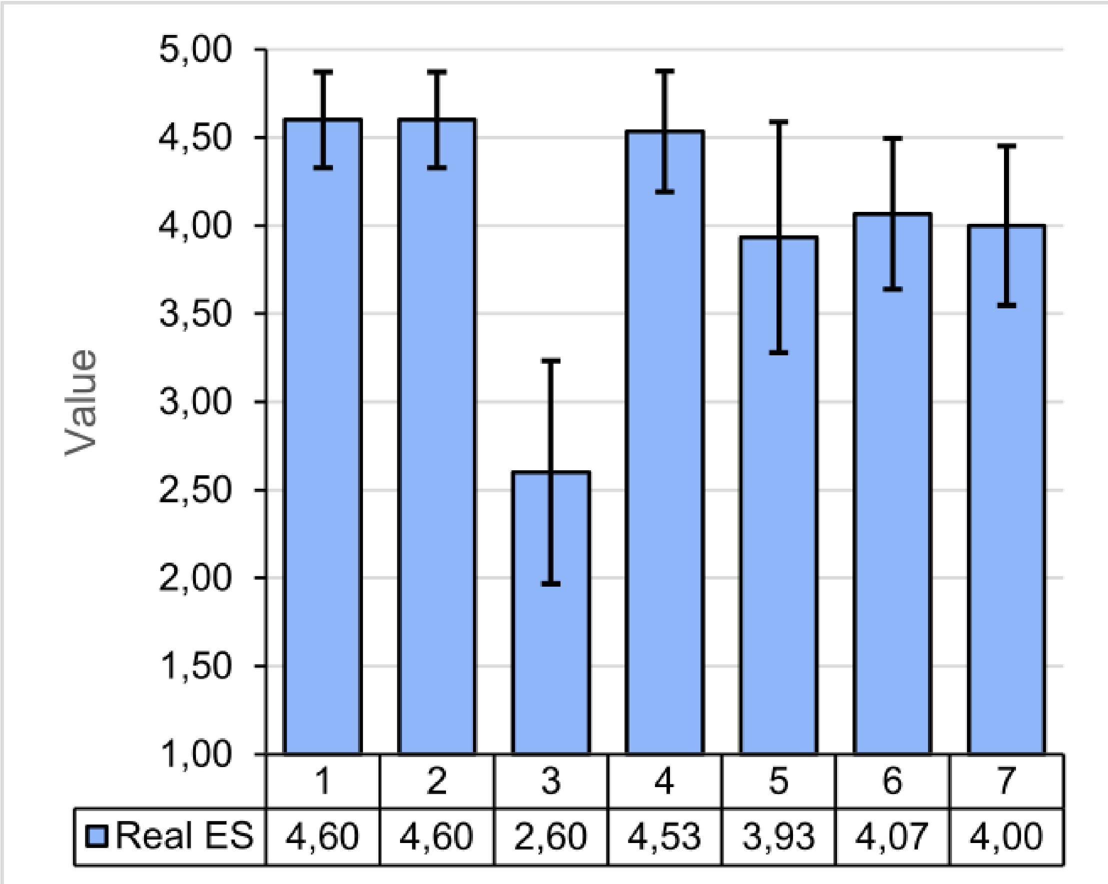


Figure 6.3: Real world results A.2.

As said, the SUS A.3.1 has been used in order to evaluate the usability of the two systems. It is a 10-statements questionnaire and as output it provides a score. The user has to assign a value between 1 and 5 to each statement, where 1 is strongly disagree and 5 is strongly agree. In the literature [77] a system with score that is grater than 68/100 is considered as usable. In the case of this work for both the systems the usability resulted as grater than 68; in particular, the value for the system composed by mockup and ManusVR is 75,5 and the value for the SenseGlove is 70. As can be see in Figure 6.4 the three questions that are responsible for the better usability of mockup with respect to SenseGlove are related to discomfort in the usage of the glove due to the exoskeleton.

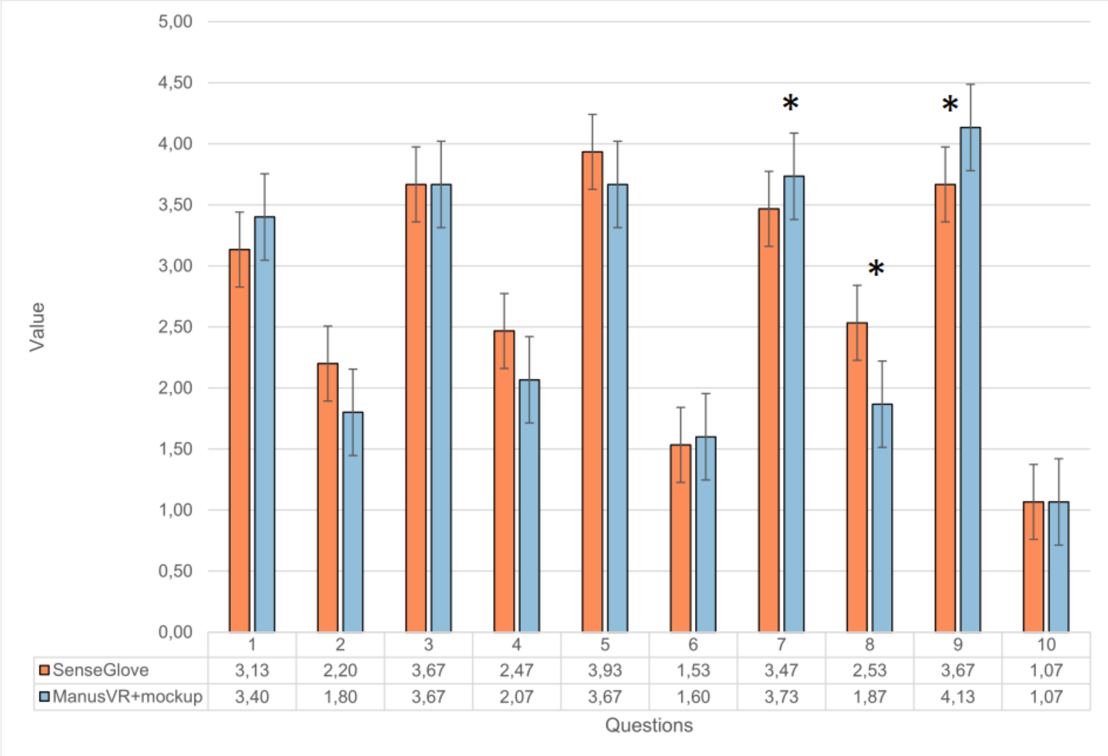
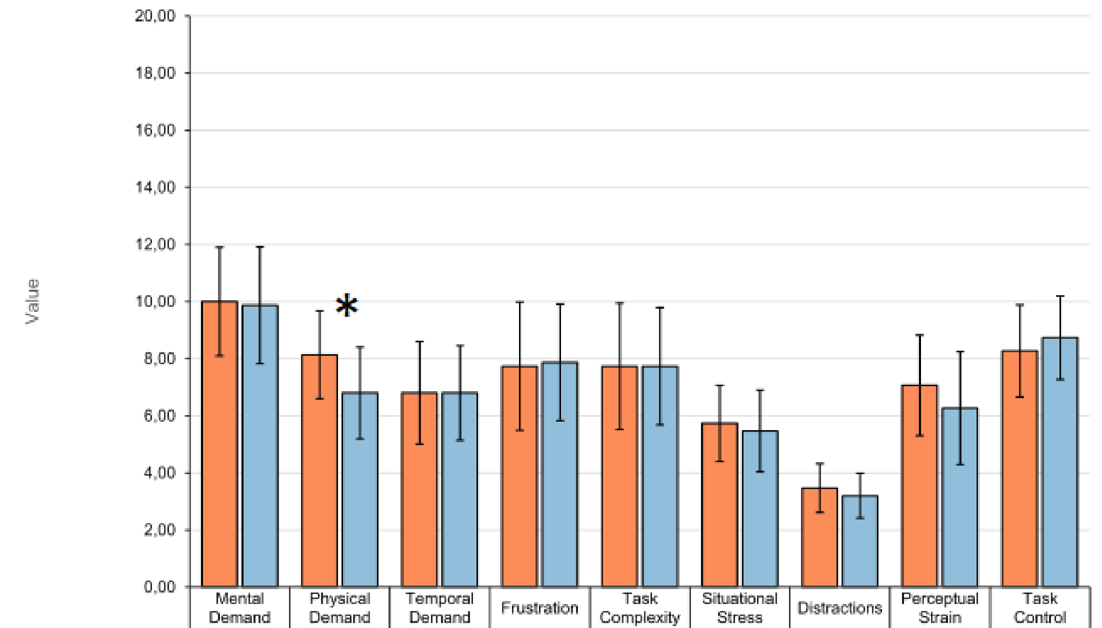


Figure 6.4: System Usability Scale graph.

Thanks to the VRUSE A.3.2 questionnaire it was possible to evaluate the sense of presence and the simulation fidelity. They have a high value and there is no significant difference between two systems; a possible interpretation is that the users felt immersed while interacting with the application independently of the system that they were wearing. It also evaluated with the SIM-TLX A.3.3 questionnaire the simulation workload. In this questionnaire the user has to give a value between 0 and 20 for several types of workload (mental demand, physical demand, temporal demand, frustration, task complexity, situational stress, distractions, perceptual strain and task control). As can be seen in Figure 6.5 all the values are almost balanced except the physical demand; this was due to the fact that, in the considered experiences, a user evaluates the whole procedure, not only the grab and in the case of ManusVR+mockup, when he/she has to perform manipulations, he/she wears only ManusVR gloves that are lighter than SenseGlove; conversely, during the screwing operations the user has to grab the mockup that is heavier than SenseGlove but he/she has to perform this operation only for a limited amount of time.



	Mental Demand	Physical Demand	Temporal Demand	Frustration	Task Complexity	Situational Stress	Distractions	Perceptual Strain	Task Control
SenseGlove	10,00	8,13	6,80	7,73	7,73	5,73	3,47	7,07	8,27
ManusVR+mockup	9,87	6,80	6,80	7,87	7,73	5,47	3,20	6,27	8,73

Figure 6.5: Workload graph.

In the UEQ A.3.4, the user had to evaluate, in a range from 1 to 7, different dimensions of the experienced system:

- attractiveness;
- perspicuity;
- efficiency;
- dependability;
- stimulation;
- novelty.

Also in this questionnaire the two systems reached high scores but no significant differences were found. In order to evaluate also the custom features (e.g., haptic perception) was created an ad-hoc section A.3.5 in the questionnaire. In Figure 6.6 can bee seen a graph that represents the value obtained in this section. Seven questions reported a significant difference between the two systems:

- Q1: this question is about the easiness of wearing. The ManusVR+mockup wins because ManusVR gloves are easy to wear since they are similar to normal gloves; conversely, SenseGlove has got exoskeleton and straps that make the hardware more complex to wear.

- Q2: the question is about the comfort during the VR experience. Although the ManusVR has got fragile wires for connecting the haptic feedback motors to power supply, the SenseGlove results heavy.

- Q3: this question is related to the manipulation of the bar and blocks. The SenseGlove offers a better experience because FFB allows more natural interactions with the VR environment.

- Q5: this question is about the shape rendered from the system while grasping a screwdriver. Also in this case the ManusVR+mockup reaches a better score due to the passive haptic feedback that comes from the 3D printed mockup.

- Q8: this question is about the feeling of the trigger of the screwdriver. Here the mockup wins because the physical trigger of the HTC Vive controller offers a better experience with respect to the FFB by SenseGlove.

- Q12,Q14,Q16,Q17: all the questions are related to the haptic perceptions; in general the SenseGlove offers a better haptic experience thanks to the precise and intense feedback of its ERM motors.

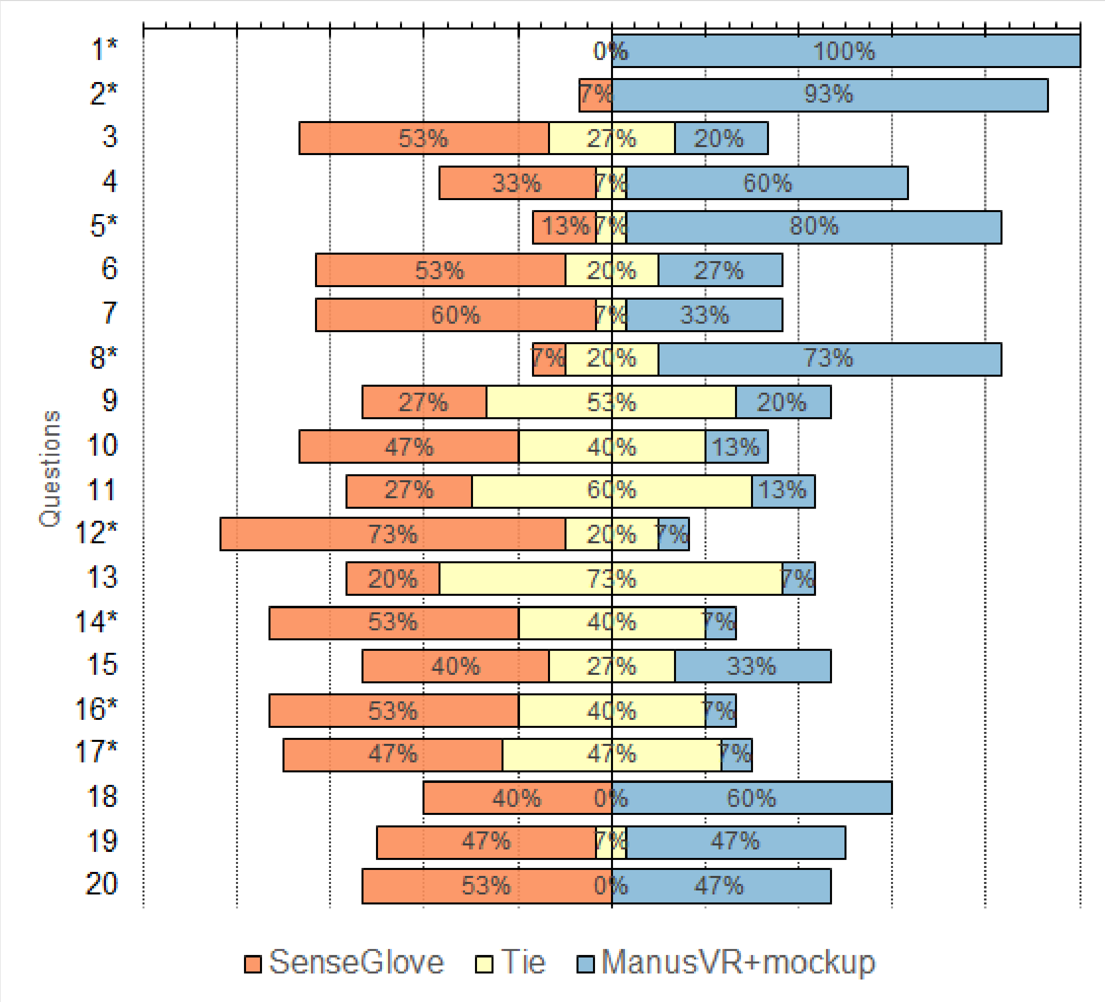


Figure 6.6: Ad-hoc questions.

For what it concerns the objective metrics the Table 6.1 can be considered; it is composed by the 8 metrics that are described in 5.1. The average value (M) for the two configuration' metrics and the relative p-values are considered. An important aspect should be considered: the system composed by ManusVR and mockup produces an higher accuracy in terms of screw's head centering and introducing a lower number of errors in terms of number of times the screwing is aborted due to slip; this result is in line with the subjective results because, with this system, the user has more control on screwing operations, in particular he/she can interact in a more natural way with the mockup with respect to SenseGlove. Another parameter to be analyzed is the time: with SenseGlove the whole experience has got a longer duration. This result could be in contrast with the outcomes of the questionnaires, because the haptic feedback in the case of SenseGlove has resulted better than the one rendered with the other system; however it is important to consider that the VR experience does not have only haptic feedback but also the visual and auditory feedback and, during the simulation by using the mockup, the user's attention relied more on visual feedback than on VTF; hence, considering that sensorimotor stimuli are slower than stimuli from the visual system [82], the mockup allows the user to perform the tasks in a lower time. Probably if the experience had been built considering only the haptic feedback the time spent for performing tasks with SenseGlove would have been lower than using mockup. Another important result that can be noticed for the system composed by ManusVR and mockup is the time change in objects manipulation before the usage the screwdriver and after; in particular the amount of time become larger when the user has got the screwdriver in his/her hand.

#	Metric	[unit]	$M_{SenseGlove}$	$M_{ManusVR+mockup}$	p-value
1	Tip centering accuracy	[mm]	33.87	23.06	**<.000**
2	N° of slips	[#]	48.14	20.29	**.019**
3	Grabbing time before first ES interaction	[s]	6.03	3.42	**.027**
4	Grabbing time after first ES interaction	[s]	6.00	16.53	**<.000**
5	Gripping screwing time	[s]	80.60	82.33	.762
6	Loose screwing time	[s]	89.92	60.96	.281
7	Time elapsed at screw tightened (Aluminum)	[s]	0.20	0.08	**<.000**
8	Time elapsed at screw tightened (Wood)	[s]	0.21	0.07	**<.00**

Table 6.1: Objective metrics.

Chapter 7

Conclusion and future works

In this work a comparison between two different configurations for performing a screwing operation has been presented. The results are promising, as both systems are considered usable based on the SUS score, even though the system composed by the ManusVR and the mockup reached an higher score. However, these technologies present also some drawbacks. In particular the experiments highlighted that the SenseGlove's hardware results difficult to wore. Conversely for the system including the ManusVR and the mockup the users complained about the quality of the haptic feedback.
In the future, it could be helpful to perform the same tasks considered in the experiments but with an upgraded technology. For instance, it could be interesting to use another glove based on exoskeleton but lighter than DK1 and easier to worn (e.g., the glove in Figure 7.1).

Figure 7.1: SenseGlove Nova [11] .

In order to provide a better feedback in the configuration with the mockup, it could be possible to put inside it some linear actuators as in the real screwdriver. It could be considered also to add new features to the system (e.g., active FFB or thermal feedback) and, to this aim, some off the devices listed below could be used.

- Dexmo Gloves: these gloves offer a FFB that can push or pull the fingers of the user (Figure 7.2). The SenseGlove, in contrast, could only stop the finger, not drag it. With SenseGlove if, for example, a user holds a balloon that increments its size over time, he/she cannot feel that his/her fingers are pulled up.

Figure 7.2: Dexmo Gloves [83].

- Phantom Omni: this device could render also a resistance of the material during the screwing process (Figure 7.3). The problem of this device is the range; in fact, if the user changes his/her position, he/she cannot feel the haptic feedback.

Figure 7.3: Phantom Omni [84].

- WEART ring: it could also be interesting to use not a glove but a ring to perform this type of task. In Figure 7.4 it is displayed a device that is able to render different types of feedback:
  - VTF: it is used for rendering the vibrations of a particular device;
  - force displacement: it is useful for representing the texture of a specific object;
  - temperature feedback: thanks to a Peltier module it is possible to render temperature, so that the user can perceive hot and cold on each fingertip.

Figure 7.4: WEART device [85] .

Appendix A

Questionairre

A.1 Domande pre-esperienza

1. ID
2. Età
3. Genere (M/F/NB)
4. Quanto spesso utilizzi/hai utilizzato strumenti per la realtà virtuale immersiva? (HTC-Vive, Oculus Rift etc...) 1 (mai), 2 (una volta), 3 (1 x mese), 4 (1 x settimana), 5 (1 x giorno)
5. Quanto spesso ti è capitato di usare un avvitatore? 1 (mai), 2 (può essere capitato), 3 (di tanto in tanto), 4 (abbastanza spesso), 5 (ogni giorno)

A.2 Domande post-uso avvitatore reale

Dai un punteggio alle seguenti affermazioni basandoti esclusivamente sulle sensazioni percepite. 1 (Completamente in disaccordo), 5 (Completamente d'accordo)

1. Ho notato differenze tra l'avvitare nel legno e l'avvitare nell'alluminio
2. Ho percepito il contatto con la testa della vite
3. Ho notato differenze nell'avvitamento di viti di lunghezza diversa
4. Ho percepito di essere arrivato a fine corsa mentre avvitavo
5. Ho percepito lo scalzo durante l'avvitamento

6. Sono riuscito ad identificare le varie fasi dell'avvitamento nel legno (contatto con testa della vite, avvitamento, scalzo, fine corsa, ecc.)?
7. Sono riuscito ad identificare le varie fasi dell'avvitamento nell'alluminio (contatto con testa della vite, avvitamento, scalzo, fine corsa, ecc.)?

A.3 Domande post-esperienza singola interfaccia

"sistema" = "guanti" oppure "mockup+manus" in VR

A.3.1 SUS

Dai un punteggio alle seguenti affermazioni. 1 (Completamente in disaccordo), 5 (Completamente d'accordo)

1. Credo che potrei usare il sistema frequentemente
2. Ho trovato il sistema eccessivamente complesso
3. Penso che il sistema sia facile da usare
4. Penso che avrei bisogno del supporto di un "tecnico" per usare il sistema
5. Ho trovato le varie funzioni del sistema ben implementate
6. Penso ci fossero troppe incongruenze nel sistema
7. Penso che la maggior parte delle persone imparerebbe ad usare un sistema come questo velocemente
8. Ho trovato il sistema scomodo da usare
9. Mi sentivo confidente/sicuro nell'usare il sistema
10. Ho avuto bisogno di imparare molte cose prima di poter utilizzare il sistema

A.3.2 VR USE

Come valuteresti le seguenti affermazioni? 1 (Completamente in disaccordo), 5 (Completamente d'accordo)

1. Avrei preferito utilizzare un altro sistema
2. La risposta del sistema agli input dell'utente erano accettabili
3. Ho trovato il sistema troppo sensibile per essere utilizzato

4. Il sistema è ideale per interagire con l'ambiente virtuale
5. La funzionalità fornita dal sistema era adeguata
6. Continuavo a sbagliare mentre interagivo con il sistema
7. Avevo il corretto livello di controllo su quello che avevo intenzione di fare
8. E' stato facile selezionare e muovere oggetti nell'ambiente virtuale
9. Il sistema è troppo complicato per essere usato in maniera efficace
10. Il feedback visivo in relazione alla simulazione era adeguato
11. Il feedback uditivo in relazione alla simulazione era adeguato
12. Il feedback aptico in relazione alla simulazione era adeguato
13. Il feeback visivo era coerente con il feedback aptico
14. Il feeback uditivo era coerente con il feedback aptico
15. Mi sono divertito ad utilizzare questo sistema
16. Riesco a vedere un grande beneficio in un sistema come questo

Fidelity

1. L'esperienza nel mondo virtuale mi è sembrata coerente con quella che avrei potuto vivere nel mondo reale
2. Avevo una corretta percezione della scala degli oggetti e dell'ambiente virtuale
3. La simulazione provata era troppo semplicistica per essere utilizzata
4. Ero impressionato dalla maniera con cui potevo interagire con la simulazione
5. La simulazione si è comportata in maniera strana, inaspettata, inusuale Ho trovato la simulazione accurata
6. La simulazione (o il sistema) sembrava bloccarsi o fermarsi a tratti
7. Gli oggetti nel mondo virtuale si muovevano in modo naturale
8. Nell'ambiente virtuale mi sono sentito disorientato
9. Avevo il giusto livello di controllo sulla simulazione

10. Penso che la qualità della simulazione abbia influito positivamente sulle mie prestazioni

11. l'ambiente virtuale era troppo complicato

12. In generale valuto la fedeltà della simulazione come: per nulla soddisfacente (1), poco soddisfacente (2), mediamente soddisfacente (3), soddisfacente (4), molto soddisfacente (5)

Presence

1. Ho avuto la sensazione di essere "immerso" nell'ambiente virtuale grazie al modo in cui i miei sensi sono stati stimolati

2. Nel mondo virtuale ho avvertito un senso di "presenza", ovvero di "trovarmi lì" durante l'esperienza

3. Non ho avuto bisogno di sentirmi immerso nell'ambiente virtuale per terminare il task assegnato

4. Non ho avuto bisogno di sentirmi presente nell'ambiente virtuale per terminare il task assegnato

Satisfaction

In generale valuto il sistema come: per nulla soddisfacente (1), poco soddisfacente (2), mediamente soddisfacente (3), soddisfacente (4), molto soddisfacente (5)

A.3.3 SIM TLX

Come valuteresti le seguenti caratteristiche in relazione al task simulato svolto? 1 (Basso) - 10 (Alto)

1. Sforzo Mentale - Quanto è stato mentalmente e percettivamente pesante svolgere il task assegnato?

2. Sforzo Fisico - Quanto è stato faticoso (fisicamente) svolgere il task assegnato?

3. Sforzo Temporale - Quanto hai sentito la pressione del tempo che passava? Hai sentito di avere fretta?

4. Frustrazione - Quanto ti sei sentit* insicur*, scoraggiat*, irritat*, stressat* o scocciat*?

5. Complessità del Task - Quanto era complesso il task assegnato?

6. Stress Situazionale - Quanto ti sei sentit* stressat* nello svolgere il task assegnato?
7. Distrazioni - Quanto ti ha distratto l'ambiente in cui ti è stato chiesto di eseguire il task?
8. Affaticamento Percettivo - Quanto scomodi/irritanti erano gli aspetti visivi/uditivi/tattili del task assegnato?
9. Controllo sul Task - Quanto è stato difficile essere in controllo delle attività mentre svolgevi il task assegnato?

A.3.4 Esperienza utente UEQ

Come valuteresti il sistema? (Scala da 1 a 7, valor medio 4)

1. Fastidioso/Piacevole
2. Incomprensibile/Comprensibile
3. Creativo/Privo di fantasia
4. Facile da apprendere/Difficile da apprendere
5. Di grande valore/Di poco valore
6. Noioso/Appassionante
7. Non interessante/Interessante
8. Imprevedibile/Prevedibile
9. Veloce/Lento
10. originale/Convenzionale
11. Ostruttivo/Di supporto
12. Buono/Scarso
13. Complicato/Facile
14. Repellente/Attraente
15. Usuale/Moderno
16. Sgradevole/Gradevole

17. Sicuro/Pericoloso
18. Stimolante/Soporifero
19. Conforme alle aspettative/Non conforme alle aspettative
20. Inefficiente/Efficiente
21. Chiaro/Confuso
22. Non pragmatico/Pragmatico
23. Ordinato/Sovraccarico (disordinato)
24. Invitante/Non invitante
25. Congeniale/Ostile
26. Conservativo/Innovativo

A.3.5 AD HOC

Come valuteresti le seguenti affermazioni basandoti esclusivamente sulle sensazioni percepite? 1 (Più i Guanti), 5 (Più il Mockup)

1. Quale sistema hai trovato più comodo/facile da indossare?
2. Quale sistema hai trovato più confortevole durante l'uso?
3. Quale sistema ti ha consentito di manipolare in maniera più naturale la barra ed i blocchetti?
4. Quale sistema ti ha permesso di interagire in maniera più naturale con l'avvitatore?
5. Quale sistema trovi che ti restituisca in maniera più fedele la forma dell'impugnatura dall'avvitatore reale?
6. Quale sistema trovi che ti restituisca una vibrazione più simile a quella fornita dall'avvitatore reale?
7. Con quale sistema hai avuto la percezione migliore della tua mano e della posizione delle dita?
8. Quale sistema riproduce in maniera più fedele il pulsante dell'avvitatore?
9. Con quale sistema sei stato in grado di distinguere meglio le differenze tra l'avvitare nel legno e nell'alluminio?

10. Con quale sistema hai percepito in maniera più fedele l'avvitamento nel legno?
11. Con quale sistema hai percepito in maniera più fedele l'avvitamento nel l'alluminio?
12. Con quale sistema hai percepito in maniera più fedele il contatto con la testa della vite?
13. Con quale sistema hai percepito in maniera più fedele differenze nell'avvitamento di viti di lunghezza diversa?
14. Con quale sistema hai percepito in maniera più fedele il fine corsa?
15. Con quale sistema hai percepito in maniera più fedele lo scalzo?
16. Con quale sistema sei stato in grado di identificare meglio le varie fasi dell'avvitamento nel legno?
17. Con quale sistema sei stato in grado di identificare meglio le varie fasi dell'avvitamento nell'alluminio?
18. Con quale sistema ti sei sentito più in controllo durante lo svolgimento del task?
19. Quale sistema ti ha permesso di svolgere il task in modo più efficiente?
20. Quale sistema hai preferito

A.4 Domande post-esperienza

Autovalutazione dello stato di salute post-simulazione [SSQ] (solo in caso di malessere).Quanto sei affetto dai seguenti sintomi in questo momento? 0 (Per nulla), 1 (Lievemente), 2 (Moderatamente), 3 (Intensamente)

1. Malessere generale
2. Affaticamento
3. Mal di testa
4. Affaticamento degli occhi
5. Difficoltà di messa a fuoco
6. Aumento della salivazione
7. Sudorazione

8. Nausea
9. Difficoltà di concentrazione
10. "Fullness of the Head" (sangue alla testa)
11. Visione offuscata
12. Vertigini con occhi aperti
13. Vertigini con occhi chiusi
14. Giramento di testa
15. Fastidio allo stomaco
16. Eruttazione
17. Commenti: (2 aspetti positivi, 2 aspetti negativi)

Bibliography

[1] Alyanne M. de Haan, Haike E. Van Stralen, Miranda Smit, Anouk Keizer, Stefan Van der Stigchel, and H. Chris Dijkerman. «No consistent cooling of the real hand in the rubber hand illusion». In: *Acta Psychologica* 179 (2017), pp. 68–77. ISSN: 0001-6918. DOI: https://doi.org/10.1016/j.actpsy.2017.07.003. URL: https://www.sciencedirect.com/science/article/pii/S000169181730001X (cit. on p. 19).

[2] and Allison M. Okamura Heather Culbertson Samuel B. Schorr. «Haptics: The Present and Future of Artificial Touch Sensations». In: 1 (Feb. 2018) (cit. on p. 20).

[3] Heather Culbertson, Samuel Schorr, and Allison Okamura. «Haptics: The Present and Future of Artificial Touch Sensation». In: *Annual Review of Control, Robotics, and Autonomous Systems* 1 (May 2018). DOI: 10.1146/annurev-control-060117-105043 (cit. on p. 20).

[4] Ildar Farkhatdinov and Jee-Hwan Ryu. «Hybrid position-position and position-speed command strategy for the bilateral teleoperation of a mobile robot». In: Nov. 2007, pp. 2442–2447. DOI: 10.1109/ICCAS.2007.4406773 (cit. on p. 21).

[5] *Tactile feedback devices: friction control and texture generation*. Accessed on 10.10.2021. URL: https://ori-nuxeo.univ-lille1.fr/nuxeo/site/esupversions/525e9085-fb68-432f-8d07-361ade9af9a8 (cit. on p. 22).

[6] Richard Skarbez, Missie Smith, and Mary C. Whitton. «Revisiting Milgram and Kishino's Reality-Virtuality Continuum». In: *Frontiers in Virtual Reality* 2 (2021), p. 27. ISSN: 2673-4192. DOI: 10.3389/frvir.2021.647997. URL: https://www.frontiersin.org/article/10.3389/frvir.2021.647997 (cit. on p. 21).

[7] Richard Skarbez, Missie Smith, and Mary C. Whitton. «Revisiting Milgram and Kishino's Reality-Virtuality Continuum». In: *Frontiers in Virtual Reality* 2 (2021), p. 27. ISSN: 2673-4192. DOI: 10.3389/frvir.2021.647997. URL: https://www.frontiersin.org/article/10.3389/frvir.2021.647997 (cit. on p. 22).

[8] Accessed on 10.10.2021. URL: https://www.polito.it/ (cit. on p. 23).

[9] Accessed on 10.10.2021. URL: https://xd.adobe.com/ideas/principles/emerging-technology/10-vr-trends-well-see-2019/ (cit. on p. 24).

[10] Accessed on 10.10.2021. URL: https://haptx.com/ (cit. on p. 25).

[11] Accessed on 10.10.2021. URL: https://www.senseglove.com/ (cit. on pp. 25, 32, 97).

[12] Accessed on 10.10.2021. URL: https://www.macevl.com/bebop (cit. on p. 25).

[13] Accessed on 10.10.2021. URL: https://www.manus-vr.com/ (cit. on p. 29).

[14] Accessed on 10.10.2021. URL: https://www.precisionmicrodrives.com/vibration-motors/linear-resonant-actuators-lras/ (cit. on p. 30).

[15] Accessed on 10.10.2021. URL: https://www.manus-vr.com/polygon (cit. on pp. 28, 30).

[16] Accessed on 10.10.2021. URL: https://www.senseglove.com/product/developers-kit/ (cit. on p. 31).

[17] Accessed on 10.10.2021. URL: https://www.precisionmicrodrives.com/content/ab-004-understanding-erm-vibration-motor-characteristics/ (cit. on pp. 31, 33).

[18] Accessed on 10.10.2021. URL: https://blog.vive.com/us/2017/02/27/steamvr/ (cit. on p. 35).

[19] Accessed on 10.10.2021. URL: https://formlabs.com/it/3d-printers/form-2/ (cit. on p. 36).

[20] Accessed on 10.10.2021. URL: https://3dprint.com/70242/blueprinter-m3/ (cit. on p. 36).

[21] Accessed on 10.10.2021. URL: https://www.3ditalyshop.it/prodotto/stampanti-3d/ultimaker/ultimaker-s3/ (cit. on p. 37).

[22] Biao Xie et al. «A Review on Virtual Reality Skill Training Applications». In: *Frontiers in Virtual Reality* 2 (2021), p. 49. ISSN: 2673-4192. DOI: 10.3389/frvir.2021.645153. URL: https://www.frontiersin.org/article/10.3389/frvir.2021.645153 (cit. on p. 39).

[23] Talib S Hussain et al. «Designing and developing effective training games for the US Navy». In: *The Interservice/Industry Training, Simulation & Education Conference (I/ITSEC)*. 1. Citeseer. 2009 (cit. on p. 39).

[24] Ylli Dalladaku, Jacob Kelley, Brycen Lacey, James Mitchiner, Braden Welsh, and Matthew Beigh. «Assessing the Effectiveness of Virtual Reality in the Training of Army Aviators». In: *Proceedings of the 2020 Annual General Donald R. Keith Memorial Capstone Conference, New York, NY*. 2020 (cit. on p. 40).

[25] Jean-Daniel Taupiac, Nancy Rodriguez, Olivier Strauss, and Martin Rabier. «Ad-hoc study on soldiers calibration procedure in virtual reality». In: *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE. 2019, pp. 190–199 (cit. on p. 40).

[26] Takayuki Nozawa, Erwin Wu, and Hideki Koike. «VR Ski Coach: Indoor Ski Training System Visualizing Difference from Leading Skier». In: *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. 2019, pp. 1341–1342. DOI: `10.1109/VR.2019.8797717` (cit. on p. 40).

[27] Jean-Luc Lugrin, Sebastian Oberdorfer, Marc Erich Latoschik, Alice Wittmann, Christian Seufert, and Silke Grafe. «VR-Assisted vs Video-Assisted Teacher Training». In: *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. 2018, pp. 625–626. DOI: `10.1109/VR.2018.8446312` (cit. on p. 40).

[28] Grégoire Richard, Thomas Pietrzak, Ferran Argelaguet, Anatole Lécuyer, and Géry Casiez. «Studying the Role of Haptic Feedback on Virtual Embodiment in a Drawing Task». In: *Frontiers in Virtual Reality* 1 (2021), p. 28. ISSN: 2673-4192. DOI: `10.3389/frvir.2020.573167`. URL: `https://www.frontiersin.org/article/10.3389/frvir.2020.573167` (cit. on p. 41).

[29] Ian Oakley, Marilyn Rose McGee, Stephen Brewster, and Philip Gray. «Putting the Feel in 'Look and Feel'». In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '00. The Hague, The Netherlands: Association for Computing Machinery, 2000, pp. 415–422. ISBN: 1581132166. DOI: `10.1145/332040.332467`. URL: `https://doi.org/10.1145/332040.332467` (cit. on p. 41).

[30] Liliana Rincon-Gonzalez, Jay P. Warren, David M. Meller, and Stephen Helms Tillery. «Haptic Interaction of Touch and Proprioception: Implications for Neuroprosthetics». In: *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 19.5 (2011), pp. 490–500. DOI: `10.1109/TNSRE.2011.2166808` (cit. on p. 41).

[31] Joshua P. Brown and Ildar Farkhatdinov. «Soft Haptic Interface based on Vibration and Particle Jamming». In: *2020 IEEE Haptics Symposium (HAPTICS)*. 2020, pp. 1–6. DOI: `10.1109/HAPTICS45997.2020.ras.HAP20.8.0698f2bb` (cit. on p. 41).

[32] Gregory Reardon, Nikolas Kastor, Yitian Shao, and Yon Visell. «Elastowave: Localized Tactile Feedback in a Soft Haptic Interface via Focused Elastic Waves». In: *2020 IEEE Haptics Symposium (HAPTICS)*. 2020, pp. 7–14. DOI: 10.1109/HAPTICS45997.2020.ras.HAP20.25.aa4d97aa (cit. on pp. 41, 42).

[33] Ge Shi et al. «Fluidic Haptic Interface for Mechano-Tactile Feedback». In: *IEEE Transactions on Haptics* 13.1 (2020), pp. 204–210. DOI: 10.1109/TOH.2020.2970056 (cit. on p. 42).

[34] Yushi Sato, Takefumi Hiraki, Naruki Tanabe, Haruka Matsukura, Daisuke Iwai, and Kosuke Sato. «Modifying Texture Perception With Pseudo-Haptic Feedback for a Projected Virtual Hand Interface». In: *IEEE Access* 8 (2020), pp. 120473–120488. DOI: 10.1109/ACCESS.2020.3006440 (cit. on p. 43).

[35] Takahiro Kawabe. «Mid-Air Action Contributes to Pseudo-Haptic Stiffness Effects». In: *IEEE Transactions on Haptics* 13.1 (2020), pp. 18–24. DOI: 10.1109/TOH.2019.2961883 (cit. on p. 43).

[36] Chyanna Wee, Kian Meng Yap, and Woan Ning Lim. «Haptic Interfaces for Virtual Reality: Challenges and Research Directions». In: *IEEE Access* 9 (2021), pp. 112145–112162. DOI: 10.1109/ACCESS.2021.3103598 (cit. on p. 43).

[37] Paul Strohmeier and Kasper Hornbæk. «Generating Haptic Textures with a Vibrotactile Actuator». In: *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. New York, NY, USA: Association for Computing Machinery, 2017, pp. 4994–5005. ISBN: 9781450346559. URL: https://doi.org/10.1145/3025453.3025812 (cit. on p. 43).

[38] Evan Strasnick, Christian Holz, Eyal Ofek, Mike Sinclair, and Hrvoje Benko. «Haptic Links: Bimanual Haptics for Virtual Reality Using Variable Stiffness Actuation». In: New York, NY, USA: Association for Computing Machinery, 2018, pp. 1–12. ISBN: 9781450356206. URL: https://doi.org/10.1145/3173574.3174218 (cit. on pp. 43, 44).

[39] Hrvoje Benko, Christian Holz, Mike Sinclair, and Eyal Ofek. «NormalTouch and TextureTouch: High-Fidelity 3D Haptic Shape Rendering on Handheld Virtual Reality Controllers». In: *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*. UIST '16. Tokyo, Japan: Association for Computing Machinery, 2016, pp. 717–728. ISBN: 9781450341899. DOI: 10.1145/2984511.2984526. URL: https://doi.org/10.1145/2984511.2984526 (cit. on p. 44).

[40] Eric Whitmire, Hrvoje Benko, Christian Holz, Eyal Ofek, and Mike Sinclair. «Haptic Revolver: Touch, Shear, Texture, and Shape Rendering on a Reconfigurable Virtual Reality Controller». In: *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. New York, NY, USA: Association for Computing Machinery, 2018, pp. 1–12. ISBN: 9781450356206. URL: `https://doi.org/10.1145/3173574.3173660` (cit. on p. 45).

[41] Inrak Choi, Eyal Ofek, Hrvoje Benko, Mike Sinclair, and Christian Holz. «CLAW: A Multifunctional Handheld Haptic Controller for Grasping, Touching, and Triggering in Virtual Reality». In: *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. New York, NY, USA: Association for Computing Machinery, 2018, pp. 1–13. ISBN: 9781450356206. URL: `https://doi.org/10.1145/3173574.3174228` (cit. on pp. 45, 46).

[42] Jaeyeon Lee, Mike Sinclair, Mar Gonzalez-Franco, Eyal Ofek, and Christian Holz. «TORC: A Virtual Reality Controller for In-Hand High-Dexterity Finger Interaction». In: *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. New York, NY, USA: Association for Computing Machinery, 2019, pp. 1–13. ISBN: 9781450359702. URL: `https://doi.org/10.1145/3290605.3300301` (cit. on pp. 46, 47).

[43] André Zenner and Antonio Krüger. «Drag:On: A Virtual Reality Controller Providing Haptic Feedback Based on Drag and Weight Shift». In: *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. New York, NY, USA: Association for Computing Machinery, 2019, pp. 1–12. ISBN: 9781450359702. URL: `https://doi.org/10.1145/3290605.3300441` (cit. on p. 47).

[44] Daniel K.Y. Chen, Jean-Baptiste Chossat, and Peter B. Shull. «HaptiVec: Presenting Haptic Feedback Vectors in Handheld Controllers Using Embedded Tactile Pin Arrays». In: *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. New York, NY, USA: Association for Computing Machinery, 2019, pp. 1–11. ISBN: 9781450359702. URL: `https://doi.org/10.1145/3290605.3300401` (cit. on pp. 47, 48).

[45] Inrak Choi, Elliot W. Hawkes, David L. Christensen, Christopher J. Ploch, and Sean Follmer. «Wolverine: A wearable haptic interface for grasping in virtual reality». In: *2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. 2016, pp. 986–993. DOI: `10.1109/IROS.2016.7759169` (cit. on p. 48).

[46] Vibol Yem and Hiroyuki Kajimoto. «Wearable tactile device using mechanical and electrical stimulation for fingertip interaction with virtual world». In: *2017 IEEE Virtual Reality (VR)*. 2017, pp. 99–104. DOI: `10.1109/VR.2017.7892236` (cit. on p. 49).

[47] Evan Pezent, Ali Israr, Majed Samad, Shea Robinson, Priyanshu Agarwal, Hrvoje Benko, and Nick Colonnese. «Tasbi: Multisensory Squeeze and Vibrotactile Wrist Haptics for Augmented and Virtual Reality». In: *2019 IEEE World Haptics Conference (WHC)*. 2019, pp. 1–6. DOI: 10.1109/WHC.2019.8816098 (cit. on p. 49).

[48] Steeven Villa Salazar, Claudio Pacchierotti, Xavier de Tinguy, Anderson Maciel, and Maud Marchal. «Altering the Stiffness, Friction, and Shape Perception of Tangible Objects in Virtual Reality Using Wearable Haptics». In: *IEEE Transactions on Haptics* 13.1 (2020), pp. 167–174. DOI: 10.1109/TOH.2020.2967389 (cit. on pp. 49, 50).

[49] Cathy Fang, Yang Zhang, Matthew Dworman, and Chris Harrison. «Wireality: Enabling Complex Tangible Geometries in Virtual Reality with Worn Multi-String Haptics». In: New York, NY, USA: Association for Computing Machinery, 2020, pp. 1–10. ISBN: 9781450367080. URL: https://doi.org/10.1145/3313831.3376470 (cit. on p. 50).

[50] Bruno Araujo, Ricardo Jota, Varun Perumal, Jia Xian Yao, Karan Singh, and Daniel Wigdor. «Snake Charmer: Physically Enabling Virtual Objects». In: *Proceedings of the TEI '16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction*. TEI '16. Eindhoven, Netherlands: Association for Computing Machinery, 2016, pp. 218–226. ISBN: 9781450335829. DOI: 10.1145/2839462.2839484. URL: https://doi.org/10.1145/2839462.2839484 (cit. on p. 51).

[51] Naoki Takizawa, Hiroaki Yano, Hiroo Iwata, Yukio Oshiro, and Nobuhiro Ohkohchi. «Encountered-Type Haptic Interface for Representation of Shape and Rigidity of 3D Virtual Objects». In: *IEEE Transactions on Haptics* 10.4 (2017), pp. 500–510. DOI: 10.1109/TOH.2017.2740934 (cit. on p. 51).

[52] Yaesol Kim, Hyun Jung Kim, and Young J. Kim. «Encountered-type haptic display for large VR environment using per-plane reachability maps». In: *Computer Animation and Virtual Worlds* 29.3-4 (2018). e1814 cav.1814, e1814. DOI: https://doi.org/10.1002/cav.1814. eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/cav.1814. URL: https://onlinelibrary.wiley.com/doi/abs/10.1002/cav.1814 (cit. on pp. 51, 52).

[53] Kotaro Yamaguchi, Ginga Kato, Yoshihiro Kuroda, Kiyoshi Kiyokawa, and Haruo Takemura. «A Non-Grounded and Encountered-Type Haptic Display Using a Drone». In: *Proceedings of the 2016 Symposium on Spatial User Interaction*. SUI '16. Tokyo, Japan: Association for Computing Machinery, 2016, pp. 43–46. ISBN: 9781450340687. DOI: 10.1145/2983310.2985746. URL: https://doi.org/10.1145/2983310.2985746 (cit. on pp. 52, 53).

[54] Matthias Hoppe, Pascal Knierim, Thomas Kosch, Markus Funk, Lauren Futami, Stefan Schneegass, Niels Henze, Albrecht Schmidt, and Tonja Machulla. «VRHapticDrones: Providing Haptics in Virtual Reality through Quadcopters». In: *Proceedings of the 17th International Conference on Mobile and Ubiquitous Multimedia*. MUM 2018. Cairo, Egypt: Association for Computing Machinery, 2018, pp. 7–18. ISBN: 9781450365949. DOI: 10.1145/3282894.3282898. URL: https://doi.org/10.1145/3282894.3282898 (cit. on pp. 52, 53).

[55] Parastoo Abtahi, Benoit Landry, Jackie (Junrui) Yang, Marco Pavone, Sean Follmer, and James A. Landay. «Beyond The Force: Using Quadcopters to Appropriate Objects and the Environment for Haptics in Virtual Reality». In: *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. New York, NY, USA: Association for Computing Machinery, 2019, pp. 1–13. ISBN: 9781450359702. URL: https://doi.org/10.1145/3290605.3300589 (cit. on pp. 53, 54).

[56] Hsin-Yu Huang, Chih-Wei Ning, Po-Yao Wang, Jen-Hao Cheng, and Lung-Pan Cheng. «Haptic-Go-Round: A Surrounding Platform for Encounter-Type Haptics in Virtual Reality Experiences». In: *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. New York, NY, USA: Association for Computing Machinery, 2020, pp. 1–10. ISBN: 9781450367080. URL: https://doi.org/10.1145/3313831.3376476 (cit. on pp. 53, 54).

[57] Keigo Matsumoto, Takeru Hashimoto, Junya Mizutani, Hibiki Yonahara, Ryohei Nagao, Takuji Narumi, Tomohiro Tanikawa, and Michitaka Hirose. «Magic Table: Deformable Props Using Visuo Haptic Redirection». In: *SIGGRAPH Asia 2017 Emerging Technologies*. SA '17. Bangkok, Thailand: Association for Computing Machinery, 2017. ISBN: 9781450354042. DOI: 10.1145/3132818.3132821. URL: https://doi.org/10.1145/3132818.3132821 (cit. on pp. 54, 55).

[58] John C. McClelland, Robert J. Teather, and Audrey Girouard. «Haptobend: Shape-Changing Passive Haptic Feedback in Virtual Reality». In: *Proceedings of the 5th Symposium on Spatial User Interaction*. SUI '17. Brighton, United Kingdom: Association for Computing Machinery, 2017, pp. 82–90. ISBN: 9781450354868. DOI: 10.1145/3131277.3132179. URL: https://doi.org/10.1145/3131277.3132179 (cit. on pp. 55, 56).

[59] Davide Calandra, F. Gabriele Pratticò, Alberto Cannavò, Luca Micelli, and Fabrizio Lamberti. «Building Reconfigurable Passive Haptic Interfaces On Demand Using Off-the-shelf Construction Bricks». In: *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. 2019, pp. 1403–1404. DOI: 10.1109/VR.2019.8797865 (cit. on pp. 55, 57).

[60] Michael White, James Gain, Ulysse Vimont, and Daniel Lochner. «The Case for Haptic Props: Shape, Weight and Vibro-Tactile Feedback». In: *Motion, Interaction and Games*. MIG '19. Newcastle upon Tyne, United Kingdom: Association for Computing Machinery, 2019. ISBN: 9781450369947. DOI: 10.1145/3359566.3360058. URL: https://doi.org/10.1145/3359566.3360058 (cit. on p. 55).

[61] Patrick L. Strandholt, Oana A. Dogaru, Niels C. Nilsson, Rolf Nordahl, and Stefania Serafin. «Knock on Wood: Combining Redirected Touching and Physical Props for Tool-Based Interaction in Virtual Reality». In: *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. New York, NY, USA: Association for Computing Machinery, 2020, pp. 1–13. ISBN: 9781450367080. URL: https://doi.org/10.1145/3313831.3376303 (cit. on pp. 55, 58).

[62] Tom Carter, Sue Ann Seah, Benjamin Long, Bruce Drinkwater, and Sriram Subramanian. «UltraHaptics: Multi-Point Mid-Air Haptic Feedback for Touch Surfaces». In: *Proceedings of the 26th Annual ACM Symposium on User Interface Software and Technology*. UIST '13. St. Andrews, Scotland, United Kingdom: Association for Computing Machinery, 2013, pp. 505–514. ISBN: 9781450322683. DOI: 10.1145/2501988.2502018. URL: https://doi.org/10.1145/2501988.2502018 (cit. on pp. 55, 58).

[63] Antti Sand, Ismo Rakkolainen, Poika Isokoski, Jari Kangas, Roope Raisamo, and Karri Palovuori. «Head-Mounted Display with Mid-Air Tactile Feedback». In: *Proceedings of the 21st ACM Symposium on Virtual Reality Software and Technology*. VRST '15. Beijing, China: Association for Computing Machinery, 2015, pp. 51–58. ISBN: 9781450339902. DOI: 10.1145/2821592.2821593. URL: https://doi.org/10.1145/2821592.2821593 (cit. on pp. 57, 59).

[64] Atsushi Matsubayashi, Yasutoshi Makino, and Hiroyuki Shinoda. «Direct Finger Manipulation of 3D Object Image with Ultrasound Haptic Feedback». In: *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. New York, NY, USA: Association for Computing Machinery, 2019, pp. 1–11. ISBN: 9781450359702. URL: https://doi.org/10.1145/3290605.3300317 (cit. on p. 57).

[65] Thomas Howard, Maud Marchal, Anatole Lécuyer, and Claudio Pacchierotti. «PUMAH: Pan-Tilt Ultrasound Mid-Air Haptics for Larger Interaction Workspace in Virtual Reality». In: *IEEE Transactions on Haptics* 13.1 (2020), pp. 38–44. DOI: 10.1109/TOH.2019.2963028 (cit. on p. 58).

[66] Ping-Hsuan Han, Chiao-En Hsieh, Yang-Sheng Chen, Jui-Chun Hsiao, Kong-Chang Lee, Sheng-Fu Ko, Kuan-Wen Chen, Chien-Hsing Chou, and Yi-Ping Hung. «AoEs: Enhancing Teleportation Experience in Immersive Environment

with Mid-Air Haptics». In: *ACM SIGGRAPH 2017 Emerging Technologies*. SIGGRAPH '17. Los Angeles, California: Association for Computing Machinery, 2017. ISBN: 9781450350129. DOI: 10.1145/3084822.3084823. URL: https://doi.org/10.1145/3084822.3084823 (cit. on p. 58).

[67] Davide Calandra, Fabrizio Lamberti, and Massimo Migliorini. «On the Usability of Consumer Locomotion Techniques in Serious Games: Comparing Arm Swinging, Treadmills and Walk-in-Place». In: *2019 IEEE 9th International Conference on Consumer Electronics (ICCE-Berlin)*. 2019, pp. 348–352. DOI: 10.1109/ICCE-Berlin47944.2019.8966165 (cit. on p. 58).

[68] Mithra Vankipuram, Kanav Kahol, Alex McLaren, and Sethuraman Panchanathan. «A virtual reality simulator for orthopedic basic skills: A design and validation study». In: *Journal of Biomedical Informatics* 43.5 (2010), pp. 661–668. ISSN: 1532-0464. DOI: https://doi.org/10.1016/j.jbi.2010.05.016. URL: https://www.sciencedirect.com/science/article/pii/S1532046410000857 (cit. on p. 59).

[69] Iñaki Díaz, Jorge Juan Gil, and Marcos Louredo. «A haptic pedal for surgery assistance». In: *Computer Methods and Programs in Biomedicine* 116.2 (2014). New methods of human-robot interaction in medical practice, pp. 97–104. ISSN: 0169-2607. DOI: https://doi.org/10.1016/j.cmpb.2013.10.010. URL: https://www.sciencedirect.com/science/article/pii/S0169260713003520 (cit. on p. 60).

[70] Florence Rogister, Caroline Salmon, Alexandre Ghuysen, Peter Andrews, Pierre Bonnet, and S. Camby. «Virtual reality surgical simulation as a tuition aid for understanding surgical temporal bone anatomy: trial on 15 ear, nose, and throat registrars». In: *B-ENT* 16 (Dec. 2020), pp. 103–108. DOI: 10.5152/B-ENT.2020.20017 (cit. on p. 60).

[71] Museok Jeong, Sungmin Lim, Taehyeong Lim, and Jeeheon Ryu. «Work-in-Progress——Is Virtual Reality Simulation Ineffective for Skill Acquisition Training?» In: *2021 7th International Conference of the Immersive Learning Research Network (iLRN)*. IEEE, May 2021. DOI: 10.23919/ilrn52045.2021.9459402. URL: https://doi.org/10.23919%2Filrn52045.2021.9459402 (cit. on pp. 60, 61).

[72] Accessed on 10.10.2021. URL: https://pace.txtgroup.com/products/extended-reality/pacelab-weavr/ (cit. on p. 63).

[73] William Mcmahan, Joseph Romano, Amal Rahuman, and Katherine Kuchenbecker. «High Frequency Acceleration Feedback Significantly Increases the Realism of Haptically Rendered Textured Surfaces». In: *Departmental Papers (MEAM)* (Mar. 2010). DOI: 10.1109/HAPTIC.2010.5444665 (cit. on p. 69).

[74] William McMahan and Katherine J. Kuchenbecker. «Haptic display of realistic tool contact via dynamically compensated control of a dedicated actuator». In: *2009 IEEE/RSJ International Conference on Intelligent Robots and Systems*. 2009, pp. 3170–3177. DOI: 10.1109/IROS.2009.5354607 (cit. on p. 69).

[75] Accessed on 10.10.2021. URL: https://www.analog.com/media/en/technical-documentation/data-sheets/ADXL345.pdf (cit. on p. 70).

[76] Accessed on 10.10.2021. URL: https://www.scuolacamerana.it/ (cit. on p. 76).

[77] *SUS Questionnaire*. Accessed on 10.10.2021. URL: https://www.usability.gov/how-to-and-tools/methods/system-usability-scale.html (cit. on pp. 84, 91).

[78] Harris, Wilson David, Vine Mark, and Samuel. «Development and validation of a simulation workload measure: the simulation task load index (SIM-TLX)». In: (2020). ISSN: 1434-9957. DOI: 10.1007/s10055-019-00422-9. URL: https://doi.org/10.1007/s10055-019-00422-9 (cit. on p. 85).

[79] Roy S. Kalawsky. «VRUSE—a computerised diagnostic tool: for usability evaluation of virtual/synthetic environment systems». In: *Applied Ergonomics* 30.1 (1999), pp. 11–25. ISSN: 0003-6870. DOI: https://doi.org/10.1016/S0003-6870(98)00047-7. URL: https://www.sciencedirect.com/science/article/pii/S0003687098000477 (cit. on p. 85).

[80] *UEQ Questionnaire*. Accessed on 10.10.2021. URL: https://www.ueq-online.org/ (cit. on p. 85).

[81] Accessed on 10.10.2021. URL: https://www.leonardocompany.com/it/home (cit. on p. 85).

[82] Adrian Ramos Peon and Domenico Prattichizzo. «Reaction times to constraint violation in haptics: comparing vibration, visual and audio stimuli». In: *2013 World Haptics Conference (WHC)*. 2013, pp. 657–661. DOI: 10.1109/WHC.2013.6548486 (cit. on p. 96).

[83] Accessed on 10.10.2021. URL: https://www.dextarobotics.com/ (cit. on p. 98).

[84] Accessed on 10.10.2021. URL: https://delfthapticslab.nl/device/phantom-omni/ (cit. on p. 99).

[85] Accessed on 10.10.2021. URL: https://www.weart.it/ (cit. on p. 99).