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Contribution to the Study of Usability and Haptic Feedback of Encountered-Type Haptic Displays

Victor Rodrigo Mercado Garcia

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L'INSTITUT NATIONAL DES
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ÉCOLE DOCTORALE N° 601
*Mathématiques et Sciences et Technologies
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Spécialité : « voir liste sur le site de votre école doctorale »

Par

Víctor MERCADO

Contribution to the Study of Usability and Haptic Feedback of Encountered-Type Haptic Displays

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A Sofía, con todo mi amor...

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TABLE OF CONTENTS

List of Figures	11
List of Tables	14
Introduction	17
Context	18
The LobbyBot Project	18
Applications of ETHDs	19
Challenges	19
Usability	19
Haptic Feedback	22
Actuator Performance	23
Thesis Roadmap	25
Contributions	26
1 Literature Review	29
1.1 Introduction	29
1.2 Definition and Fundamental Notions	30
1.2.1 ETHD Definition	30
1.2.2 ETHD System Scheme	31
1.2.3 Contact and Rendering Area	32
1.3 History of ETHD Research	32
1.4 ETHDs Feature Devices	34
1.4.1 ETHD Actuator Types	34
1.4.1.1 Grounded	35
1.4.1.2 Ungrounded	36
1.4.2 Surface Display Type	40
1.4.2.1 Static Surface	41
1.4.2.2 Dynamic Surface	42
1.4.3 Tracking Systems	45

TABLE OF CONTENTS

1.4.3.1	Built-In Tracking System	46
1.4.3.2	Marker-based Tracking System	47
1.4.3.3	Marker-Independent Tracking System	47
1.4.4	Visual Display Devices	48
1.4.4.1	Screens	48
1.4.4.2	Virtual Reality Head-Mounted Display	49
1.4.4.3	Augmented and Mixed Reality Head-Mounted Displays	50
1.5	Haptic Feedback Related to ETHD Interaction	50
1.5.1	Haptic Sensory Information Provided by ETHDs	50
1.5.2	Haptic Exploration	53
1.5.2.1	Contact	54
1.5.2.2	Haptic Exploratory Procedures	54
1.6	Interaction with ETHDs	58
1.6.1	Virtual Environment Interaction	58
1.6.1.1	Surface Exploration	58
1.6.1.2	Object Manipulation	59
1.6.1.3	Teleoperation	60
1.6.1.4	Locomotion	61
1.6.2	Interaction Techniques for ETHDs	61
1.7	Applications	62
1.7.1	Medicine	63
1.7.2	Industry	64
1.7.3	Entertainment	64
1.7.4	Research	66
1.8	Discussion	67
1.8.1	Hardware Approaches for ETHDs	68
1.8.2	Interaction with ETHDs	69
1.9	Conclusion	70
2	Improving User Safety for ETHDs	73
2.1	Design Space	74
2.1.1	Design Space Organization	74
2.1.1.1	Block What	74
2.1.1.2	Block When	75

2.1.1.3	Block How	75
2.1.2	Safety Techniques	76
2.2	Preliminary Evaluation	81
2.2.1	Evaluation Criteria	81
2.2.2	Participants	84
2.2.3	Experimental Procedure	84
2.2.4	Results	85
2.3	Discussion	88
2.3.1	Results Discussion	88
2.3.1.1	Safety Subscale	90
2.3.1.2	Immersion Subscale	90
2.3.2	Design Recommendations	91
2.4	Conclusion	92
3	Designing Interaction Techniques for Surface Exploration with ETHDs	95
3.1	Interaction Technique Design	96
3.1.1	Design Space	97
3.1.1.1	Input	97
3.1.1.2	Movement Control	98
3.1.1.3	Displacement	98
3.1.1.4	Contact	98
3.1.2	Interaction Techniques	99
3.1.2.1	Swipe	99
3.1.2.2	Clutch	100
3.1.2.3	Drag	100
3.1.2.4	Bubble	102
3.1.2.5	Follow	102
3.2	Use Case	103
3.3	User Study	104
3.3.1	Experimental Setup	104
3.3.2	Procedure	104
3.3.3	Experimental Design	105
3.3.4	Collected Data and Population	105
3.4	Results	106

TABLE OF CONTENTS

3.5	Discussion	109
3.6	Conclusion	112
4	Allowing Large, Multi-Textured Surface Rendering for ETHDs	113
4.1	The ENTROPiA Approach	114
4.1.1	Rotating Props	116
4.1.2	Interaction Technique	116
4.2	Proof of Concept	118
4.2.1	Setup	118
4.2.2	Scenario	119
4.3	User Study	119
4.3.1	Experimental Design	120
4.3.2	Experimental Setup	121
4.3.3	Procedure	122
4.3.4	Collected Data and Population	122
4.4	Results	123
4.4.1	Experiment	123
4.4.2	Questionnaire	123
4.5	Discussion	124
4.6	Conclusion	126
5	Allowing Object Manipulation with ETHDs	127
5.1	The ALFRED Approach	128
5.1.1	System components	130
5.1.2	Safety	132
5.2	Illustrative Setup	133
5.2.1	System prototype	133
5.2.2	Interaction Technique	133
5.2.3	Illustration 1: Manipulating one object between known positions	135
5.2.4	Illustration 2: Mapping one tangible to many virtual objects	136
5.2.5	Illustration 3: Freely manipulating one of many objects	137
5.3	Evaluation	138
5.4	Results	140
5.5	Discussion	141
5.6	Conclusion	143

6 Conclusion	145
6.1 Contributions	145
6.2 Perspectives	146
6.2.1 Short Term Perspectives	146
6.2.2 Long-Term Perspectives	147
A Author's Publications	151
A.1 Peer-Reviewed Journals	151
A.2 Peer-Reviewed Conferences	151
A.3 In Preparation	151
A.4 Miscellaneous	152
Résumé Étendu en Français	152
Bibliography	165

LIST OF FIGURES

1	ETHD Original Concept	17
2	LobbyBot Project	18
3	Application domains for ETHDs	20
4	Thesis Roadmap	25
1.1	Schematics of an ETHD System and User Interaction	32
1.2	Contact and Rendering Areas of an ETHD System	33
1.3	ETHD Actuator Type Taxonomy	35
1.4	Grounded Robotic Arm ETHD Scheme	36
1.5	Grounded Robotic Arm ETHD Example	36
1.6	Grounded Fixed Platform ETHD Scheme	37
1.7	Grounded Fixed Platform ETHD Example	37
1.8	Ungrounded Unmanned Air Vehicle ETHD Scheme	38
1.9	Ungrounded Unmanned Air Vehicle ETHD Example	38
1.10	Ungrounded Mobile Platform ETHD Scheme	39
1.11	Ungrounded Mobile Platform ETHD Example	39
1.12	Ungrounded Wearable ETHD Scheme	40
1.13	Ungrounded Wearable ETHD Example	40
1.14	Static Flat Surface Display	41
1.15	Static Volume Surface Display	42
1.16	Dynamic Pin-Array Surface Display	43
1.17	Dynamic Mid-Air Haptic Surface Display	44
1.18	Dynamic Actuated Surface Display	44
1.19	Dynamic Ring/Thimble Surface Display	45
1.20	Dynamic Fluid-Based Surface Display	46
1.21	Dynamic Rotatory Surface Display	46
1.22	Locomotion Platform	47
1.23	Built-in Tracking System	48
1.24	Marker-based Tracking System	48
1.25	Marker-independent Tracking System	49

1.26	Screen Display	50
1.27	VR-based HMD	52
1.28	AR-based HMD	53
1.29	Surface Contact Example	54
1.30	Lateral Motion Example	55
1.31	Pressure Example	56
1.32	Contour Following Example	56
1.33	Static Contact Example	57
1.34	Part Motion Test & Function Test Example	58
1.35	Surface Exploration Example	59
1.36	Object Manipulation Example	60
1.37	Teleoperation Example	61
1.38	Locomotion Example	61
1.39	Medicine Application Example	63
1.40	Industrial Application Example	65
1.41	Entertainment Application Example	66
1.42	Research Application Example	67
1.43	ETHD Timeline	68
2.1	Safety Techniques for ETHDs	82
2.2	Average Scores for Perceived Safety and Immersion Criteria	86
2.3	Average Scores for the Safety and Immersion Subscales	89
3.1	System Setup	96
3.2	Design Space	97
3.3	Interaction Techniques Diagram	101
3.4	Use-Case Scenario	103
3.5	Resulting Participants' Paintings	106
3.6	User Experience Questionnaire Results	107
4.1	ENTROPiA System Setup	114
4.2	ENTROPiA Principle	115
4.3	ENTROPiA Prop	117
4.4	ENTROPiA Interaction Technique	118
4.5	Use-Case Scenario	119

LIST OF FIGURES

4.6	Use-Case Scenario Materials	120
4.7	Experimental Prop	121
4.8	Experimental Setup	122
4.9	User Study Results	124
5.1	Alfred System Scheme	128
5.2	Alfred Concept	129
5.3	Alfred Interaction Technique	132
5.4	Alfred Control Scheme	134
5.5	Assembly Line Use-Case Scenario	135
5.6	Bar Use-Case Scenario	136
5.7	Jar Stacking Use-Case Scenario	137
5.8	User Motion Diagram	140
5.9	Evaluation Results	142
A.1	Applications	154
A.2	Chemin de These	155
A.3	Techniques de sécurité pour des ICI	158
A.4	Techniques d'interaction	160
A.5	Le principe ENTROPiA	162
A.6	Illustration conceptuelle d'Alfred	163

LIST OF TABLES

1	Contributions and Research Questions Table	26
1.1	Literature Summary Table	51
1.2	Haptic Exploratory Procedures	59
1.3	Interaction Tasks	62
1.4	Interactions Present in ETHD Applications	66
1.5	Actuator Types Present in ETHD Applications	67
2.1	Design Space	77
2.2	Principal Component Analysis Results	87
2.3	Average Scores	88
3.1	Performance Results	106

INTRODUCTION

Virtual reality (VR) technologies allow us to get immersed into mesmerizing virtual worlds. Haptic technologies born from robotics have increased the immersion in these virtual worlds by providing the sensation of touch within them. Years of research on haptics, robotics, and interaction in VR have led to the development of a category of devices called encountered-type haptic displays (ETHDs). ETHDs allow users to touch surfaces in a virtual environment (VE) by placing a tangible surface in a position where users can voluntarily engage and disengage contact with it as naturally as they would do in a real environment. In a few words, ETHDs provide "on-demand" haptic feedback, looking to be at the right place and time, so users can come in contact with them. ETHDs usually rely on head-mounted displays (HMDs) for "hiding" the robotic device from the users' view and thus giving them the sensation of actually touching the surfaces they see in a VE. A diagram depicting the ETHD's core concept can be seen in Figure 1.

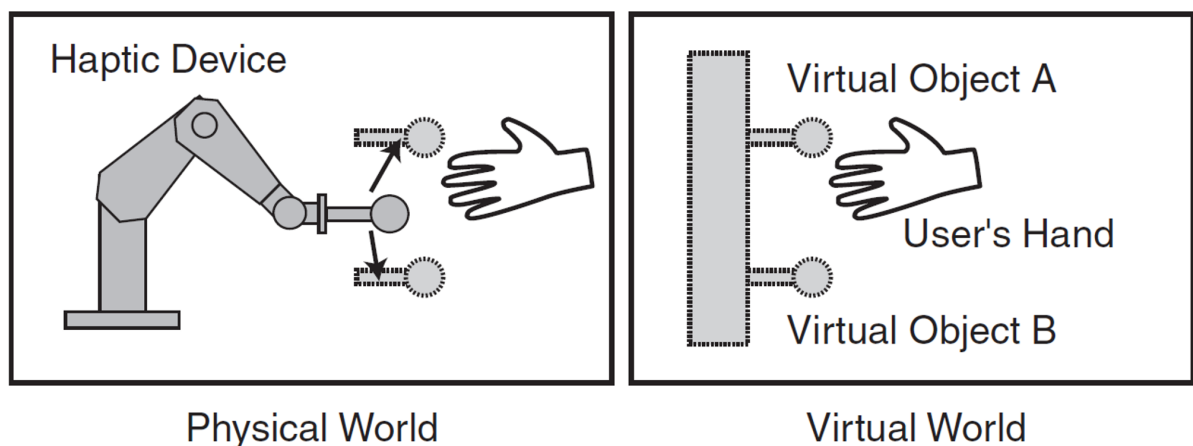


Figure 1 – The ETHD Original Concept from Yokokohji et al [1]. The core concept behind ETHDs relies on having a haptic device placing surfaces that could be encountered by users whenever they wanted to touch a surface in VR. The haptic device (ETHD) is occluded by an immersive VE which also provides a use context to the device's rendered haptic feedback.

This thesis, entitled "*Contribution to the Study of Usability and Haptic Feedback of Encountered-Type Haptic Displays*" presents a series of research works aiming to leverage the usability and haptic feedback capabilities of ETHDs. These research works were created to address the current limitations of these haptic displays by designing interaction techniques that increase the system's usability and by conceiving new haptic feedback paradigms to increase the possibilities of touch sensations rendered by ETHDs.

Context

The LobbyBot Project

This thesis was developed under the frame of the French National Research Agency (ANR) LobbyBot project. The LobbyBot project consisted in developing an ETHD system that could be integrated in an industrial application for automobile interior prototyping. This system was intended to be used to recreate an automobile cockpit for faster prototyping in VR for the Renault Group, a French automobile company (see Figure 2). In this fast prototyping process, designers had to explore with their sense of touch the different materials, shapes, and objects that could be arranged in a virtual automobile interior that could be easily configured in VR. This new paradigm was conceived as a means to save the Renault Group costs in budget and time for fabricating actual automobile cockpits that are exclusively used for prototyping purposes.



Figure 2 – The LobbyBot project setup. This figure showcases the "LobbyBot" prototype using a Universal Robots UR5 robotic arm and a multi-textured prop for rendering haptic feedback when users explored a car cockpit in virtual reality with their sense of touch.

The project assembled a consortium consisting of four partners: The Renault Group who was in charge of providing the use-case scenario and problematic, the Laboratory of

Digital Sciences of Nantes (LS2N) who was in charge of the ETHD's path-planning algorithm for avoiding collisions with users, the National Institute for Research in Computer Science and Automation (Inria) who was in charge of conceiving interaction techniques for increasing the prototype's usability, and CLARTE who was in charge of integrating the aforementioned contributions from all the other partners to implement the ETHD system.

Applications of ETHDs

ETHD applications range from industry [2], [3], entertainment [4], [5], medicine [6], [7] and research [8], [9] purposes. In all these cases, users expect to "encounter" a surface to touch or manipulate in a VE. In the case of industrial applications, these devices are considered for virtual prototyping that requires to have haptic feedback in several locations in order to recreate workspaces or objects to be manipulated. In the case of entertainment, ETHDs are used to recreate elements that can come in contact with the users when interacting with a ludic VE [10]. In the case of medicine, ETHDs are often used for remote body-palpation and surgery practice [6]. The use of ETHDs for research purposes often looks for leveraging the devices' capabilities for rendering more complex surfaces and objects. Some of these examples are illustrated in Figure 3.

Challenges

In order to leverage the capabilities of ETHDs, several challenges must be addressed in different dimensions such as: **usability**, **haptic feedback**, and **actuator performance**. The challenges are divided into research questions (RQ) that this thesis addresses in the following chapters, namely; (RQ1) User safety; (RQ2) Interaction techniques for surface exploration; (RQ3) Large surface rendering; (RQ4) Multiple surface rendering; (RQ5) Object manipulation; (RQ6) Control algorithm optimization; (RQ7) Actuator diversification. These questions are further presented below.

Challenge 1: Usability

Usability is defined by Nielsen as a quality attribute "that assesses how easy user interfaces are to use" [11]. ETHDs require interaction techniques that are easy to learn, efficient on the device control, and easy to understand. In addition, these systems should

ETHD Application Domains

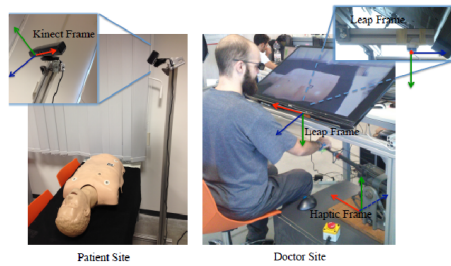
Entertainment



Industry



Medicine



Research

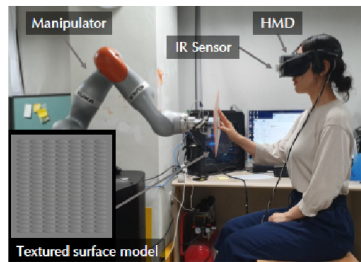


Figure 3 – Application domains for ETHDs. These developments have been present in four different domains. This figure present one example for each domain: (1) entertainment [4], (2) industry [2], (3) medicine [6], and (4) research [8].

provide feedback to diminish user error in order to avoid involuntary collisions between users and haptic display that could compromise user safety.

Research Question 1: User Safety for ETHDs

The concern about avoiding unexpected collisions with users has been present ever since the early days of ETHD research [12], [13]. Measures for addressing this issue normally consider path-planning algorithms that help the robotic display to actively avoid the user in cases where both user and device could come into contact involuntarily [14]. However, the use of path-planning normally yields the device's movement slower. The delay between users' actions and comments normally affects usability and users' perceived immersion in the VE, and thus, it has been recognized as an issue to be addressed by the research community [2]. As an alternative to solutions exclusively relying on path-planning for avoiding collisions with users, the work of Abtahi et al. [15] considered the use of warning signs when users get close enough to the haptic display. Research concerning user safety for ETHD systems needs to look for usability strategies that indicate users the device's presence and behavior. This could help users to avoid any undesired contact that could break their' trust in the system and perceived immersion in the VE.

Research Question 2: Interaction Techniques Design for Surface Exploration with ETHDs

There is no fixed technique or standard procedure to use an ETHD for exploring surfaces in VR. The lack of interaction techniques for surface exploration could be due to the assumption that these devices are supposed to yield haptic feedback by relying exclusively on the device's capability of positioning itself in several points of the VE [2], [16]. Several efforts have been undertaken in the field of human-machine interaction (HMI) and haptics for optimizing surface rendering for haptic displays [17], [18]. Surface exploration is an active research topic in haptics. The ETHD field is mostly concerned with this activity since these devices allow unconstrained experiences to users when they desire to touch object in VEs. Surface exploration could then be improved with the design of proper interaction techniques that can adapt to the ETHD's workspace and surface display's haptic rendering capabilities.

Challenge 2: Haptic Feedback

Haptic feedback for ETHDs largely depends on the surface display attached to its end-effector. Depending on the complexity of this display, ETHDs can render haptic feedback ranging from a flat surface to a graspable object. There is a need for optimizing surface displays that could be adapted to a wide variety of stimuli provided in a VE.

Research Question 3: Large Surface Rendering for ETHDs

Since the surface display's size often constraints the size of the surface that ETHDs can render in a VE, these devices have to use control algorithms and interaction techniques to make haptic rendering as efficient as possible. However, these two solutions are not enough when the surface display cannot provide a wide assortment of haptic sensations.

Previous research works have considered the use of large surfaces and actuators to give users the sensation that they are continuously touching a large surface using an ETHD [3], [19]. However, increasing the size of the rendered surface imposes challenges for displacing and placing the surface display in an encountered location. Research is needed to optimize surface rendering by pairing the surface display's rendering capabilities with those of the actuators' in matters of displacing the surface display.

Research Question 4: Multiple Texture Rendering for ETHDs

The increased complexity of VEs in matters of surface's materials and shapes that can be portrayed within them poses a challenge for the haptics community. In the case of ETHDs, shape and texture rendering is often constrained to the size and shape of the surface display attached to the device's end-effector. Researchers have considered the use of multi-sided surface displays to provide different textures for interaction [2], [20]. Surface displays such as the one in Drif et al. [21] and Kim et al. [8] have used vibration and rotation respectively to provide different textures sensations. Despite these efforts, there is a need for a surface display that could be complex enough for rendering a larger variety of textures that matches a large assortment of textured objects and surfaces in a VE.

Research Question 5: Object Manipulation for ETHDs

Object manipulation remains as a challenge to be properly addressed by the ETHD research community. Normally, the shape display is often attached to the robotic ac-

tuator’s end-effector and haptic exploratory procedures related to grasping and object manipulation are limited by the way the shape display is attached. In addition, shape displays normally found in ETHD literature can only render a partial part of the object that is being represented in a VE and thus limiting object grasping and manipulation [15]. Wearable approaches have addressed object grasping [22], [23]. Nevertheless, while its size is smaller, the shape display’s attachment to the actuator is still present. This attachment constraints full object manipulation. Efforts addressing this challenge come mostly from ungrounded unmanned air vehicles (UAVs). UAV-based ETHDs have the advantage of being the actual shape displays and not having a constrained workspace [5], [15], [24]. However, shape rendering is mostly limited to the shape of the cage surrounding the UAV. Consequently, further research is needed for giving users an unconstrained sensation of grasping and manipulating objects rendered by an ETHD.

Challenge 3: Actuator Performance

ETHD’s **actuator performance** needs to be optimized to increase the haptic rendering capabilities of these devices. Since ETHDs are used to displace a surface from one point to another, research has also been present to address the challenge of displacing a surface in the most efficient way possible. The research community has been looking for increasing ETHD actuator performance through two main methods: designing control algorithms that optimize the surface display’s trajectory when moving through the device’s workspace, and the diversification of the actuator types to exploit the ETHD’s hardware configuration.

Research Question 6: Control Algorithms for ETHDs

One of the major challenges for ETHDs refers to control planning algorithms that consider three factors: (1) placing the surface display in an encounter position aligned with a virtual surface, (2) avoiding any contact with the users’ body when the device is in movement, and (3) achieving the former two points in an optimal speed that does not interfere with the users’ perceived immersion in the VE.

Researchers have been proposing methods for path-planning and user avoidance ever since the first ETHD implementations up to nowadays [9], [14], [25], [26]. However, these path-planning algorithms are limited to the actuator types they consider for their own research. being adapted to other types of actuators. Research for control algorithms re-

quires taking into account more complex interactions between users and ETHDs, while also permitting to address speed performance issues in order to avoid breaking users' immersion.

Research Question 7: Actuator Diversification for ETHDs

The ETHD research community has been looking for expanding the actuator type diversity in both grounded and ungrounded categories. Grounded robotic arms are still widely used in research and industrial purposes. In the grounded field, fixed platforms have become an alternative to render more "personalized" haptic feedback primarily in matters of texture rendering. However, these devices have limited workspace that might only be useful for specific scenarios.

Current research has been exploring new actuator approaches in the ungrounded field concerning UAVs, mobile platforms, and wearable devices. Current limitations for ungrounded devices concern limited force and surface rendering. In addition, the surface displays held by these actuators are limited in their size and shape. This is due to the fact that these surfaces need to be continuously moved and placed in a wider variety of places in comparison to their grounded counterparts. Research efforts for increasing the diversity of actuator types for ETHDs could consider augmenting the rendering capabilities of the surface displays attached to these devices.

Relationship between Research Questions

Interestingly, the presented research questions for ETHDs are deeply related between themselves. For example, an interaction technique that could increase the system's usability could also enhance the haptic feedback capabilities of the device with the use of visual feedback that gives the illusion of touching a larger surface. Control algorithms for ETHDs do not only ensure a faster and more precise device's placement, but they also take into account user safety by actively avoiding any contact with any part of the users' body. For instance, a novel ETHD hardware approach could profit from advancements in usability by using an interaction technique complemented with a sophisticated control algorithm dedicated to maintain users safety when interacting with the device.

Due to the relationship between the aforementioned research questions, the contributions presented in this thesis address several research questions at the same time through the dimensions of **usability**, **haptic feedback**, and **actuator performance**. Further

details about the thesis’ roadmap for addressing these research questions are presented in the next section.

Thesis Roadmap

The two main axes considered for the contributions of this thesis are **usability** and **haptic feedback**. These research axes and the contributions they comprised are illustrated in Figure 4 and showcased in Table 1.

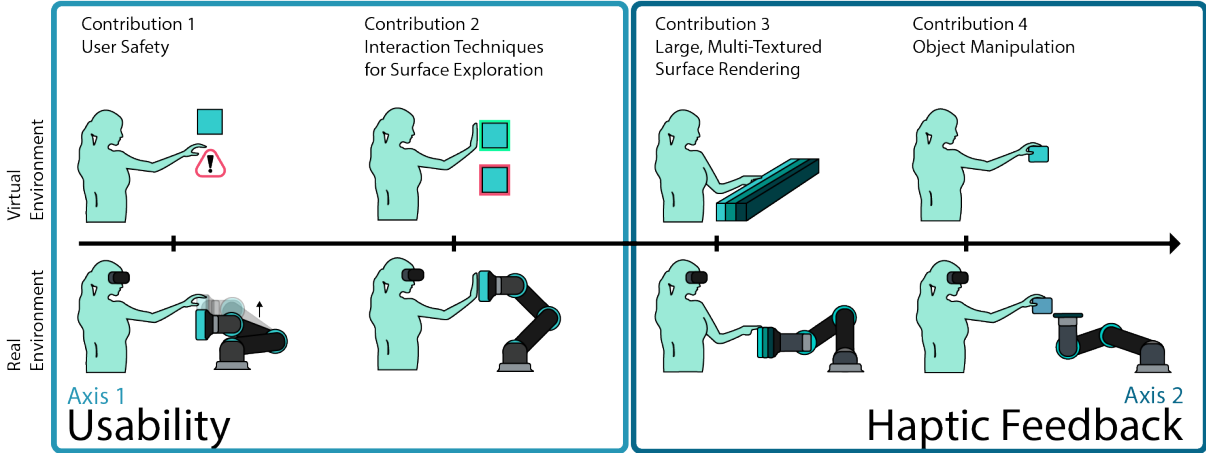


Figure 4 – The Thesis Roadmap. This figure showcases how the contributions are organized according to the research axes and their presentation in the thesis’s chapters.

The first two contributions in this thesis aim to leverage ETHDs usability. The usability axis first presents a contribution (C1) consisting of a set of safety techniques based in visual feedback for balancing users’ immersion and perceived safety. Then, this axis presents a contribution (C2) that addresses large surface exploration with a set of interaction techniques designed to optimize surface rendering with ETHDs.

The next two contributions in this thesis aim to leverage ETHDs haptic feedback. The haptic feedback axis first introduces an approach (C3) for large, multi-texture surface rendering with ETHDs. This approach is based on a rotating prop which is span and moved below user’s finger to give the sensation of touching a large surface. The second contribution in this axis presents an approach for object manipulation with ETHDs (C4). This approach allows creating, destroying, and reconfiguring objects in VEs using a detachable tangible from the ETHD’s surface display.

Contribution/ Research Question (RQ)	RQ1	RQ2	RQ3	RQ4	RQ5	RQ6	RQ7
(C1) Improving User Safety for ETHDs	X	X					
(C2) Design of Interaction Techniques for Surface Exploration for ETHDs		X	X				
(C3) Allowing Large, Multi-Textured Surface Rendering for ETHDs			X	X			
(C4) Allowing Object Manipulation for ETHDs					X	X	

Table 1 – Contributions and Research Questions Table. This table portrays how each contribution presented in this thesis addresses the various research questions.

Table 1 presents the relationship between the contributions and research questions. The presented contributions address at least two research questions in different combinations. This doctoral project was focused particularly on the research questions related to software aspects of ETHDs. As such, it did not answer RQ7 directly. In the following chapters the details about how the contributions addressed the research questions will be presented.

Contributions

The contributions of this thesis are depicted in chapters which are described hereby:

Chapter 1 presents a literature review concerning ETHDs. In the first part, the history of these devices is narrated. The second part presents an analysis of hardware used for these devices. The third section presents the types of haptic perception used in literature. The fourth part discusses application scenarios for ETHDs. The literature review concludes with a discussion about the presented research works.

Chapter 2 presents a set of safety techniques for ETHDs based on visual feedback (C1). This chapter introduces a design space for safety techniques using visual feedback in order to raise awareness of the robot’s state and reduce potential unintended collisions. The dimensions of the design space focus on what and when the feedback is displayed and how it protects the user. Using this design space, a set of 18 techniques were developed exploring variations of the three dimensions. An evaluation questionnaire focusing on immersion and perceived safety was designed and evaluated by a group of experts, which was used to provide a first assessment of the proposed techniques.

Chapter 3 presents the design and evaluation of interaction techniques for surface exploration with ETHDs (C2). The chapter introduces first a design space for conceiving interaction techniques that consider features such as input, movement control, displacement and contact. Then, five interaction techniques conceived from this design space are presented, namely: swipe, clutch, drag, and follow. A user-study was designed to assess

the performance of these techniques in a painting task where users touched a large flat surface. Results suggested the lead of drag and clutch techniques in users' global preference and the painting task performance.

Chapter 4 presents a novel approach called ENTROPiA (Encountered-Type Rotating Prop Approach) to increase the contact area and textures provided by ETHDs (C3). This approach renders large surfaces and multiple textures through the use of a rotating prop approach that couples the prop's rotation and position with the users' hand position when exploring a large textured surface in VR. A use-case scenario was designed for contextualizing this approach. Later, a user-study was conducted to validate the approach haptic rendering performance.

Chapter 5 presents the Alfred approach for object manipulation with ETHDs (C4). The chapter starts by introducing the approach and by describing its main components. The Alfred approach presents four key features: (1) infinite re-spawn of virtual objects, (2) removal of virtual objects, (3) multiple virtual object mapping, and (4) free reconfiguration of the VE. Alfred integrates an interaction technique for object selection, manipulation, and release. A set of illustrative scenarios depict Alfred's key features in an assembly line, bar, and jar-stacking environments. An evaluation concerning the speed of the system is presented. Finally, results are presented and discussed.

Chapter 6 concludes the thesis manuscript summarizing the thesis contributions as well as providing perspectives for future work for ETHDs.

LITERATURE REVIEW

1.1 Introduction

This chapter presents a literature review of the research carried out in the ETHD field since its conceptualization to the present day. This review is mostly focused on VR simulations and haptic feedback for hand-interaction. The purpose of this review is to provide a better understanding of the different hardware, haptic feedback, interactions, and application domains used in these systems. To achieve this purpose, we firstly propose a definition for ETHDs to use it as the base of the literature analysis. Then, a brief history of these devices is presented along a timeline with timestamps related to the innovations in this field. Later, the literature review analyzes the hardware found in the literature and classifies it based on a taxonomy dedicated to ETHDs actuator types. Next, this review compares and classifies the research works in terms of haptic feedback, interaction, and applications. Finally, the review's discussion analyzes the research works based on the features presented in the chapter's previous sections.

In summary, the contributions presented in this literature review are the following:

- A definition for Encountered-Type Haptic Displays.
- An actuator-type taxonomy for ETHDs.
- A literature analysis considering actuator types, surface displays, tracking systems, visual displays, haptic feedback, interactions, and applications.

The remainder of this chapter is structured as follows: Section 1.2 discusses the definition and fundamental notions of ETHDs. Section 1.3 narrates the ETHDs history. Section 1.4 presents a survey in matters of feature devices comprising the haptic device itself as well as tracking systems and visual displays. Section 1.5 discusses the haptic perception involved through different ETHD types. The application scenarios for ETHDs are presented in Section 1.7. Interaction techniques for ETHDs are discussed in Section 1.6. A general discussion and conclusion are presented in Section 1.8 and 1.9 respectively.

1.2 Definition and Fundamental Notions

1.2.1 ETHD Definition

There have been multiple names and notions associated with ETHD technologies. McNeely [12] first proposed the concept of "robotic graphics", a term that consists of a robotic system that could provide haptic feedback in a virtual simulation. The feature of robotic graphics relies on the fact that the device itself is disguised or integrated into a VE to provide haptic feedback exclusively when contact occurs in the simulation. Tachi et al. [13] conceptualized a *haptic space* that consisted in a shape approximation device integrated with an active environment display. Their system relied on having a robotic device to place and rotate a shape as a means to display elements of a VE.

The ETHD term was first coined in the work by Yokokohoji et al. [1]. In this work, an ETHD is presented as a system that tracks users' hands and places the haptic display in a location where the user could encounter it. This concept is derived from the implementations and theoretical proposals of McNeely [12], Tachi et al. [13] and Hirota & Hirose [27]. While a formal definition has not been established by the research community, researchers in this field often mention several characteristics that an ETHD should have such as no connections between users' hands and a manipulator, no mechanical constraints to users' hands, and a mechanical detachment from touching areas in free space motion.

Based on these concepts, we propose a formal definition of ETHDs which is presented hereby:

Definition

In the context of human interaction with a virtual or remote environment, an Encountered-Type Haptic Display is a device capable of placing a part of itself or in its entirety in an encountered location that allows users to have the sensation of voluntarily eliciting haptic feedback with that environment at a proper time and location.

Under this definition, we preserve the original concepts of a device capable of positioning a haptic display according to the user's location and providing haptic feedback exclusively when the user is encountering an element in a virtual simulation [1], [12],

[14]. This definition was also adapted for comprehending wearable ETHDs, that unlike common wearable haptic displays in which the surface display, nor any other part of the device, is in constant contact with the user. This definition also adapts to more recent approaches such as mobile platform ETHDs [28]–[32] and UAV-based ETHDs [9], [10], [24], [33].

1.2.2 ETHD System Scheme

We propose a scheme for ETHDs systems considering the user in the interaction loop. This scheme is comprised by different modules which are listed below and displayed in Figure 1.1.

- *Actuator*: this module refers to the robotic actuator that places the surface display in an encountered location.
- *Surface Display*: this module is the hardware element that renders the surface that is displaced by an actuator system.
- *Tracking*: this module consists in acknowledging the user’s position for the ETHD to place itself on an encounter position according to a feature represented in the workspace.
- *Haptic Feedback*: this module concerns the moment when users make contact with the ETHD and receive haptic feedback from the system.
- *Visual Display*: this module comprises the device that provides the visual feedback which is given in synchrony with the haptic one. While most of the ETHDs presented in the literature use an HMD to hide the actual haptic display, there are research works that use a real environment that is manipulated through teleoperation.
- *Workspace*: this module represents the physical volume of space where the user and the physical ETHD system modules perform the task in the simulation environment.
- *Simulation Environment*: this module represents the environment where the user and ETHD system interact under a contextualized task. This environment can be either virtual or real depending on the task context.
- *Interaction*: this module comprises the way of interacting with the ETHD system and the way the task is carried out by the user.

The aforementioned modules are analyzed and discussed through this review to better

understand ETHDs through the perspective of feature devices, haptic perception, interaction and applications.

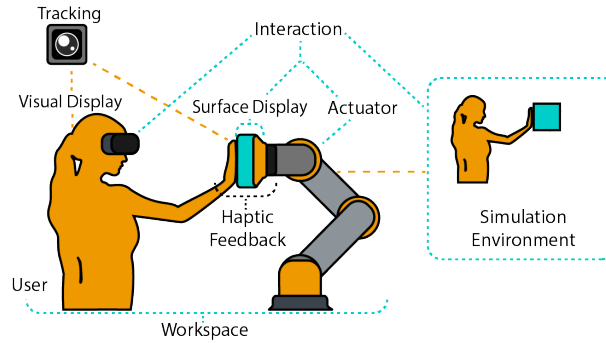


Figure 1.1 – Schematics of an ETHD system and user interaction. An ETHD system is integrated by a user tracking system, the haptic display hardware, and the environment where simulation occurs. Interaction techniques guide the user to contact the rendered shape.

1.2.3 Contact and Rendering Area

Haptic Feedback in ETHDs mostly relies on contact with a surface held and translated by a robotic actuator. The amount of surface that can be touched in a simulation depends on two factors which are listed below and displayed in Figure 1.2.

- *Contact Area*: this area refers to the space that the user can be in contact during a specific time in the haptic simulation rendered by the ETHD system.
- *Rendering Area*: this area refers to the space covered by the ETHD hardware during the interaction with the user. This comprises the hardware’s range of mobility for placing the surface display in an encountered position.

These concepts are recovered through the review for better explaining the capabilities of ETHDs at the moment of rendering haptic feedback.

1.3 History of ETHD Research

The history of ETHDs began with the conceptualization of a robotic system as a haptic rendering part of a VR simulation by McNeely [12] in 1993. The main premise of McNeely’s conceptual device was to provide the freedom of not having contact on parts where there was no necessity to have any type of haptic stimulation. This premise

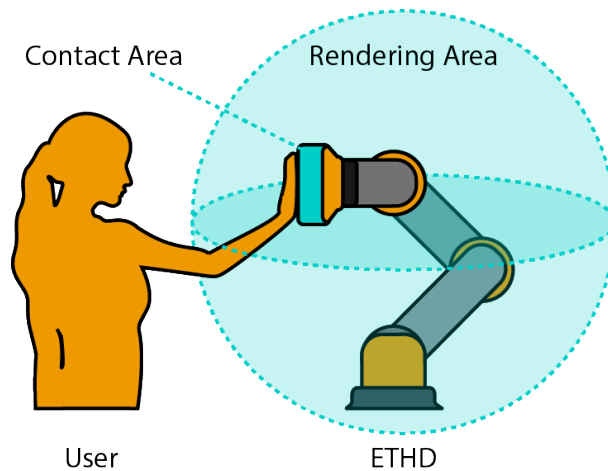


Figure 1.2 – Contact and rendering areas of an ETHD system. An ETHD system depends on two different areas referring to the amount of surface that can be touched during a simulation and the range of mobility and placement that the actuator can provide. The contact area refers to what users can touch. The rendering area refers to the actuator’s mobility range.

contrasted with other paradigms such as worn-type and held-type haptic interfaces that can obstruct or limit users’ motion range. The works of Hirota & Hirose [27] (1993) and Tachi et al. (1994) [13] are also considered as pioneer works related to conceptualizing and implementing an ETHD according to Yokokohji et al. [1].

The sum of the former works’ ideas and proposals led Yokokohji et al. [1] to propose the term ETHD as the theoretical framework of their What You can See is What You can Feel (WYSIWYF) display in the late 90’s. As their predecessors, this research work followed the principle of providing free movement to users until the moment of engaging contact with an element displayed in a VE. The WYSIWYF proposed by Yokokohji et al. considered the use of an HMD to present the VE in their simulation. However, their prototype used an LCD screen for the aforementioned purpose.

The decade of the 2000’s was focused on increasing the contact and rendering area for ETHDs, allowing curved-surface rendering, and developing path planning algorithms. These algorithms were integrated into ETHD research to avoid any involuntary contact with the user [14]. In this decade, multi-finger interaction was also integrated into ETHDs by Yokokohji et al. [34]. During this decade, VEs were conceived to provide use-case scenarios for the newly created rendering techniques [35], [36]. Most of the VEs during this time were displayed on screens[1], [14], [34]. However, some research works present prototypes using HMDs [28], [37].

The democratization of HMDs during the 2010s decade led to more complex environments through the virtuality-reality continuum [38], [39]. In addition, progress in actuator technologies yielded the use of a larger assort of devices used as ETHDs for more complex tasks such as juggling [40], medical palpation [6], [41] and surgical simulations [42]. UAV technologies brought new possibilities, leading research towards to developing ungrounded ETHDs starting with the work of Yamaguchi et al. [10]. Multi-sided end-effectors were introduced in the work of Araujo et al. [20]. The efforts in the latest years usually incorporate commercial VR headsets [5], [10], [15], [22], [43], [44]

This approach allowed giving different types of haptic feedback such as multiple textures, temperatures, and functions integrated in buttons and touch-screens. Mobile platform systems were conceived to expand the category of ungrounded ETHDs beginning by the work of Siu et al. [29].

The history of ETHD research has been defined by the hardware evolution through time, not only in matters of robotic systems but also in visual displays and tracking systems. This has permitted a notable diversity on the hardware used to implement this type of haptic displays. Further comments about ETHDs history discussion can be found in Section 1.8.

1.4 ETHDs Feature Devices

In this section, a review of ETHD feature devices is presented. This section comprises descriptions of the different existing types of ETHDs actuators, surface display, tracking systems and visual display devices. A summary of this section can be seen in Table 1.1. This table also includes the applications for each of the reviewed papers in this chapter.

1.4.1 ETHD Actuator Types

The following subsection will discuss different types of actuators for ETHDs according to classification criteria based on the devices used to provide encountered haptic feedback.

- *Grounded*. This category comprises devices that are placed on a grounded surface (e.g. the floor, a base). Research efforts can be classified on robotic arms and fixed platforms.
- *Ungrounded*. This category comprises ETHDs that are based on movable supports such as UAVs, mobile platforms, and wearable devices.

A taxonomy presenting this classification as well as the subdivisions for the grounded and ungrounded categories is presented in Figure 1.3.

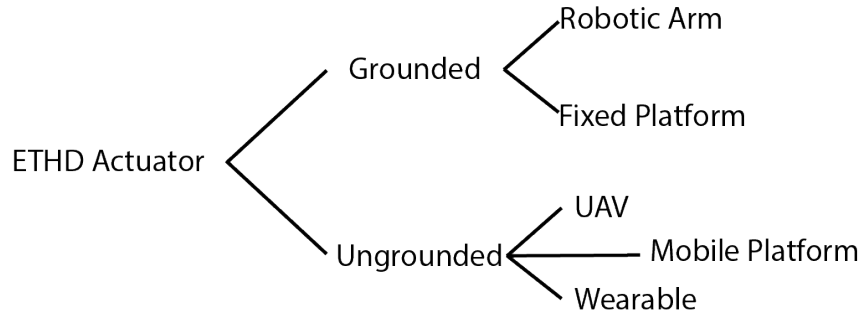


Figure 1.3 – ETHD Actuator Type Taxonomy. This diagram displays the actuator type classification for ETHDs used through the review. Overall, ETHD actuator type can be classified in two main categories: grounded and ungrounded

1.4.1.1 Grounded

This type of ETHDs uses robotic actuators to spatially locate the haptic surface display for an encountered-type approach. These devices can comprise industrial robotic arms [1], [2], [19], [20], [25], [34], [44]–[47], commercial haptic interfaces [35], [36], [38], [48], [49], and specially designed actuators for rendering haptic feedback [6], [21], [28], [34], [37], [39], [41], [42], [50]–[54]. Based on the reviewed research work we propose two categories for classifying grounded ETHDs: robotic arms and fixed platforms.

Robotic Arms This actuator type category comprises ETHDs that use joint-based actuators that position the surface display in a particular position of the workspace. These comprise industrial robotic arms, commercial haptic interfaces and personalized joint-based actuator type. One example is the Snake Charmer system from Araujo et al. [20], which holds a multi-textured surface display at the surface display for rendering the sensation of touching different surfaces in a VE. Other examples can be found in the work of [1]–[3], [6], [8], [19], [26], [38], [40], [43], [44], [47], [53], [55], [56]. A diagram of this actuator type type can be seen in Figure 1.4 and an example of this actuator type can be seen in Figure 1.5.

Fixed Platform This category refers to grounded ETHDs based on platforms displaced by robotic actuators to encounter users [3], [4], [39], [41], [42], [51], [52], [54]. An example

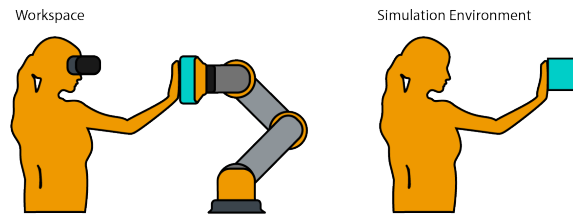


Figure 1.4 – Grounded Robotic Arm ETHD. This ETHD actuator type consists of a robot holding a shape display that represents a part of an object to be touched in the haptic rendering process.

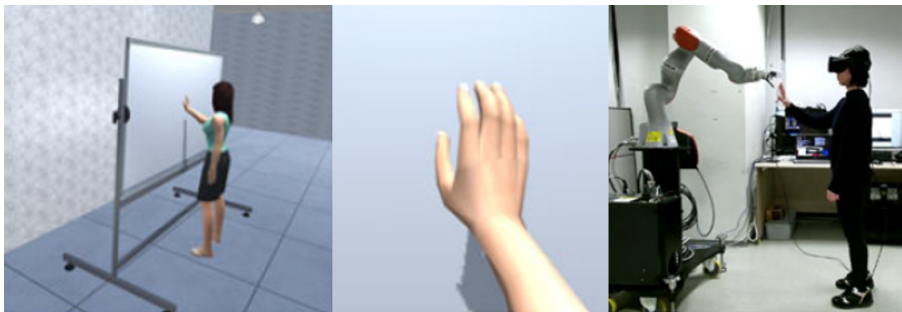


Figure 1.5 – Grounded robotic arm ETHD presented by Kim et al. [26]. This research work presents an ETHD using a robotic arm as the main actuator that brings the static surface display to the encounter position. This system was used to simulate contact with doors, walls, and boards (as seen in this figure) in a VE.

of this approach is the work of Tsujita et al. [42] that consisted of a moving platform containing a magneto-rheological fluid simulating human tissue that served a surgical training system (further details in Section 1.7). Another example of this approach comes from Takagi et al. [7] who designed an ETHD where users could interact with a touchscreen and a stylus to receive haptic feedback when manipulating objects. Iwata et al. developed a grounded locomotion platform that could bring users' feet support through a surface available at the position and moment where users stepped [37]. A diagram of this actuator type can be seen in Figure 1.6 and an example of this actuator type can be seen in Figure 1.7.

1.4.1.2 Ungrounded

Ungrounded ETHDs are not constrained to an anchor position to render haptic feedback. Ungrounded ETHDs comprise UAVs (such as drones) [5], [9], [10], [15], [24], [33], mobile platform [28]–[32] and wearable ETHDs [22], [23], [57]. Hereby we present a de-

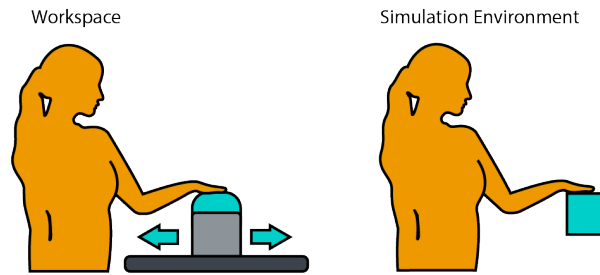


Figure 1.6 – Grounded Fixed Platform ETHD. This ETHD actuator type consists of an encountered-type surface display displaced by robotic actuators over a fixed two-dimensional platform.

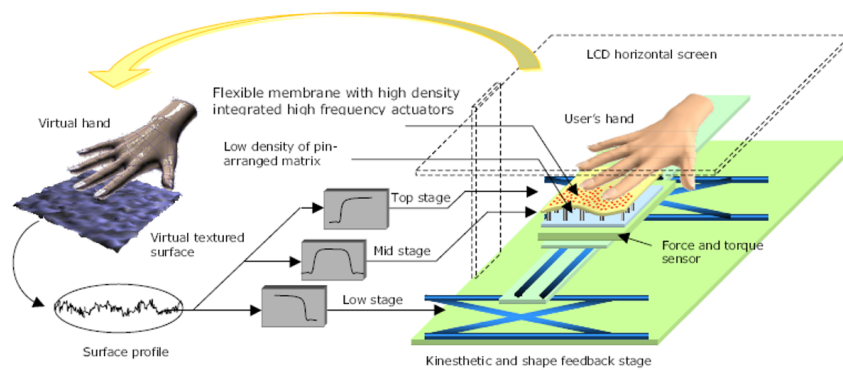


Figure 1.7 – Grounded Fixed Platform ETHD proposed by Drif et al. [21]. This research work presents an ETHD using a grounded fixed platform that moves a surface display capable of simulating different surfaces by vibrating a membrane under different frequencies when users enter in contact with it.

tailed description of other works related to each ungrounded ETHDs category:

Unmanned Air Vehicles This category refers to ungrounded ETHDs that rely on a UAV to displace the contact area through a defined rendering area such as the ETHD developed by Yamaguchi et al. [10] for rendering stiffness feedback. A diagram of this actuator type can be seen in Figure 1.8. Recent research work has been using UAVs and their properties to exploit the encounter between the user and haptic device [58]. Researchers in this particular type of ETHDs argue that UAVs possess more freedom at the moment of positioning themselves with respect to the user. This type of research has been appearing recently in the field since authors argue that it is more feasible to develop an encountered-type interface with the overall mobility of a drone [10], [24], [58]. Other examples of this approach can be found in the works of [5], [9], [15], [33]. Figure 1.9 depicts

an example of this category.

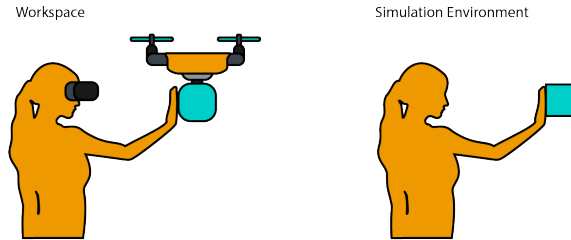


Figure 1.8 – Ungrounded Unmanned Air Vehicle ETHD. This ETHD actuator type consists on a surface held and brought to an encountered position by a UAV.



Figure 1.9 – Ungrounded UAV ETHD proposed by Hoppe et al. [5]. This research work presents an ETHD using an ungrounded UAV holding a static surface display that served as the part that physically represented the surfaces to touch in their VE.

Mobile Platform This category refers to ungrounded ETHDs primarily based on shape displays attached to a mobile base that permits them to displace through the rendering area such as the work of Fitzgerald et al. [30]. The most common approach for these devices consists in a mobile pin-array and a tracking system that permits the system to place itself under the users' hands. A diagram of this actuator type can be seen in Figure 1.10. Another approach is the mobile platform designed by Iwata et al. [28] which consists of mobile pads displacing around the users while they walk in a VE. Mobile platforms can also displace static surfaces such as the recent research works of Gonzalez et al. [31] and Suzuki et al. [32] In the former, a small tangible volume is displaced whereas in the latter bigger volumes such as walls and chairs are moved by mobile platforms. Figure 1.11 depicts an example of this category. The work of Bouzbib et al. introduces an ETHD that displaces wide platforms holding tracked tangible elements in an environment displayed in VR [59].

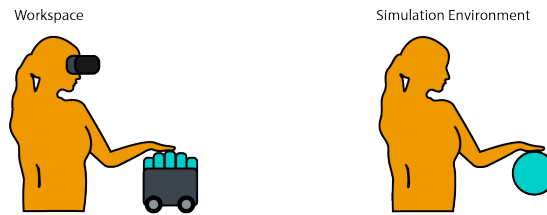


Figure 1.10 – Ungrounded Mobile Platform ETHD. This ETHD actuator type consists of a surface display brought to an encountered position by a mobile system.

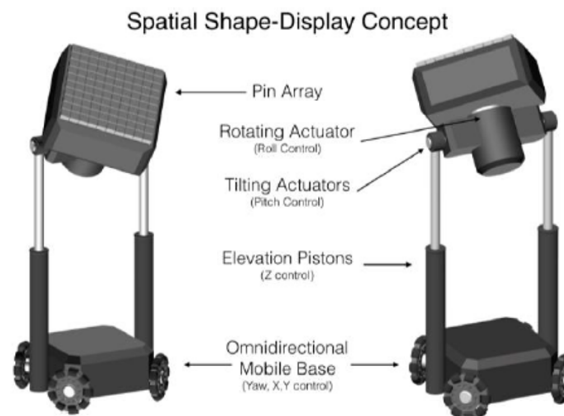


Figure 1.11 – Ungrounded Mobile Platform ETHD proposed by Fitzgerald et al. [30]. This research work uses an ungrounded mobile platform ETHD that held a pin-array surface display that permitted to recreate several shapes to touch around a large workspace area.

Wearable This category refers to ungrounded ETHDs that are mounted over the user's hand but never in direct contact with the palm, thus they can bring a tangible element in an encounter position (see Figure 1.12). A clear example is the work of De Tinguy et al. [22]. In this work, the device actuator is mounted over the hand instead of being placed directly under the hand palm, as seen in Figure 1.13. Another example of this approach is seen in the work of Kovacs et al. [60]. Wearable ETHDs possess the freedom of being ungrounded devices and at the same time, they can provide encountered-type contact with their hand-mounted but mobile surface display. The main difference between this type of wearable ETHDs against the traditional approach [61] is that the users' palm is not in direct contact with the device actuator nor with any surface whatsoever. This feature allows users to engage and disengage haptic exploration in a voluntary manner which accurately corresponds with haptic exploration in real environments. The actuator configuration of wearable ETHDs allows users to feel a sensation of grasping an object without the risk of breaking their immersion process by touching the actuator and providing haptic feedback

that does not correspond with the interactive element in a simulation. Other example of these devices can be found in [23], [57].

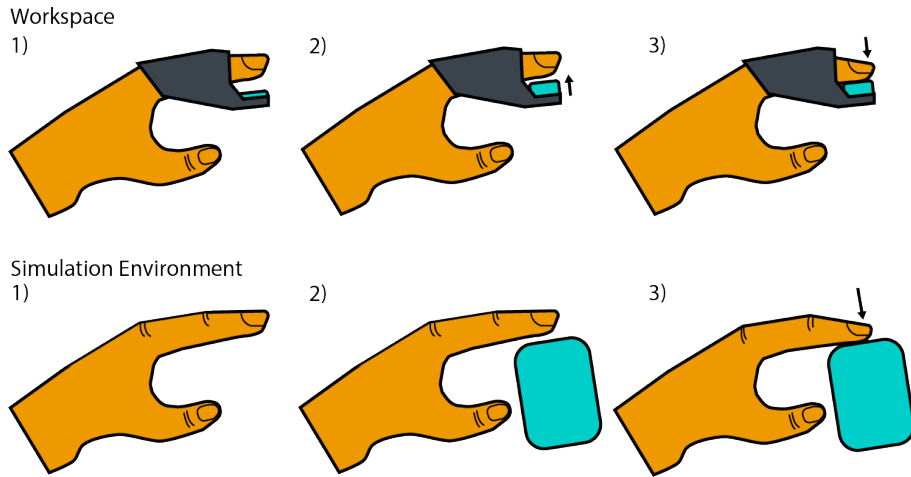


Figure 1.12 – Ungrounded Wearable ETHD. This type of ETHD hardware consists of a wearable system that provides encountered-type haptic feedback to the user. Unlike other types of wearable haptic displays, the surface rendered by these devices is not in constant contact with the user. The rendered surfaces exclusively positions itself to be voluntarily touched by the user during the simulation.

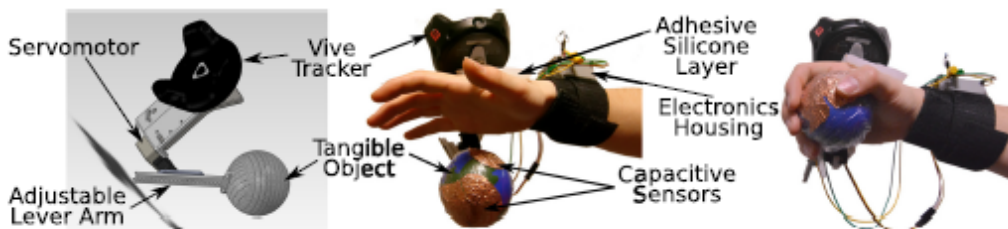


Figure 1.13 – Ungrounded Wearable ETHD proposed by De Tinguy et al. [22]. The device consists of a system mounted over the user’s hand that uses an actuator holding a tangible object that can be brought in an encounter position for the user.

1.4.2 Surface Display Type

A fundamental part in ETHDs is the way these devices are capable of rendering the different shapes and surfaces they present in a virtual simulation. Depending on their purpose, these devices can have a static or dynamic surface display. The two categories are described below:

1.4.2.1 Static Surface

These devices can only represent one shape or surface that cannot change during the virtual simulation. This surface display type can be divided into flat surfaces, volumes, buttons, and switches. A description of these sub-categories is presented hereby:

Flat Surfaces This type of surface comprises static flat tangible surfaces that can be touched in a virtual environment normally as a part of an object [1], [24], [26], [47]. ETHDs can also profit from multi-sided end-effectors for rendering different textures in flat surfaces as seen in [2], [20].

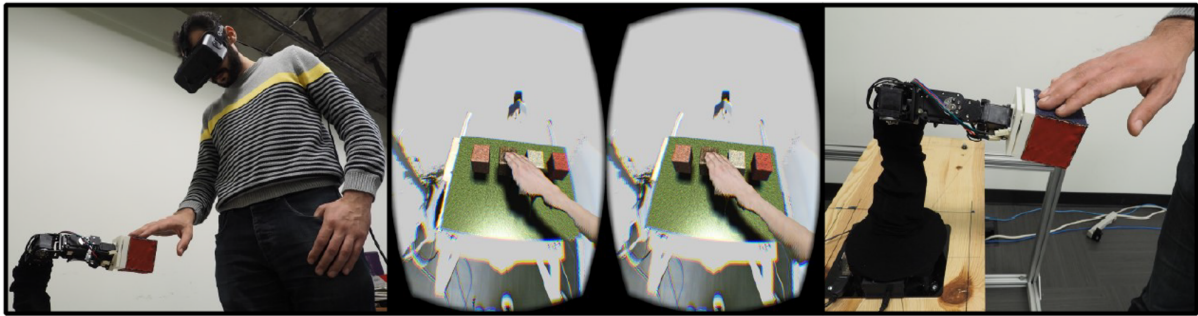


Figure 1.14 – The multiple flat surface display presented by Araujo et al. [20]. This research work presented a multi-sided tangible that presented one texture for each of its faces. This permitted to render a wide assortment of flat surfaces in the use-case scenarios presented in this research.

Volumes This type of surface permits users to touch and enclose a full volume brought into an encountered position. This approach has been present in recent research in [4], [15], [22], [31], [32], [39], [40], [43], [44], [59], [60]. Ungrounded UAV ETHDs [5], [9], [10], [15], [33] are considered in this category since they use a part of themselves or present a graspable volume in order to be manipulated by the user.

Buttons and Switches This type of surface pretends to recreate actual buttons and switches used for teleoperation. The usage of these elements has been considered ever since ETHDs' earliest days [12], [13]. Research works that consider this sub-type of surface displays are: [14], [25], [45], [56].



Figure 1.15 – The volume shape display presented by Abtahi et al. [15]. This research work profits from the cage surrounding the UAV by using it as a shape display for representing objects that can be grasped in their use-case scenario.

1.4.2.2 Dynamic Surface

This type of shape displays are capable of dynamically render different volumes and shapes through a virtual simulation. Several sub-categories have been identified in this review such as pin-arrays, mid-air haptics, actuated surfaces, ring/thimble surface displays, fluid-based surface displays, rotatory surface displays, and locomotion platforms. A description of these sub-categories is presented hereby:

Pin-Arrays This type of surface display is mostly used in ungrounded mobile platform-based ETHDs as seen in [29], [30]. This surface display type consists of an array of pins that level themselves at several altitudes to render different shapes. This kind of haptic display permits as well to render different shapes through physical reconfiguration and the usage of visuo-haptic illusions [62]. Research is moving towards increasing the resolution of these pin-arrays to produce more realistic and refined shape rendering [63].

Mid-Air Haptics This type of surface display has gained more importance in the haptic field in recent years [64], [65]. The work of Furumoto et al. [54] uses several mid-air haptic displays disposed behind, at the sides, and below a tangible object (balloon) to displace it in several points in space to later be encountered by the user. Howard et al. propose a 2 degrees-of-freedom (DOF) ETHD that uses a mid-air haptic surface display that is capable of rendering several tangible volumes. An example of this surface display type integrated to an ETHD can be seen in Figure 1.17.

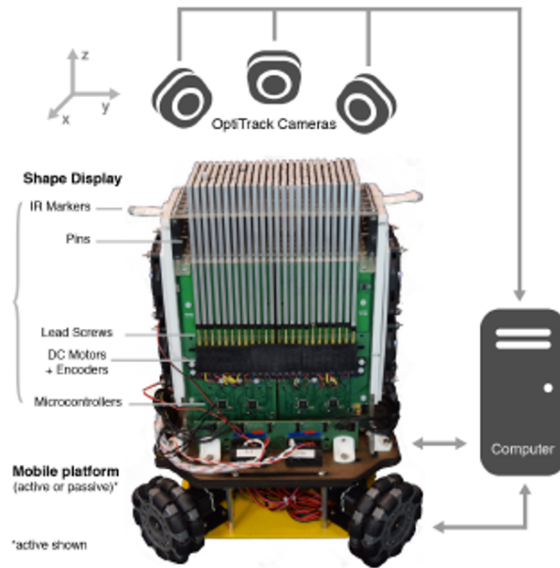


Figure 1.16 – The pin-array surface display presented by Siu et al. [29]. This research work used a pin-array to display several shapes that could be encountered by users with the help of a wheeled system that permitted the system to move the surface display.

Actuated Surfaces This type of surface display profit from actuators to actively displace the surface in contact with the user to render different volumes and shapes [6], [23], [34], [38], [57]. In the case of the Nakagawara et al. [23] wearable exo-skeleton ETHD, the plates under users' fingers adjust themselves in a specific height that permits to render a shape that a slave hand is simultaneously touching during the virtual simulation. Drif et al. [21] used a vibratory mechanism coupled to a fixed platform ETHD. This device rendered different haptic sensations based on a range of frequency vibrations produced by a robotic mechanism. Haptic feedback integrated to screens [7], [41], permitted to render different shapes by adjusting the position and rotation of the screen while users made contact with it.

Ring/Thimble Surface Displays This type of surface display refers to shape displays primarily based on ring systems connected to a robotic actuator. The principle of their functioning relies on inserting the finger into the ring and displacing the former to touch a virtual surface (see Figure 1.19). The displays used a tracking system to avoid unexpected ring collisions with the users' fingers. One example of a ring/thimble system is found in the work of Kuchenbecker et al. [36] which use a thimble attached to a haptic display to

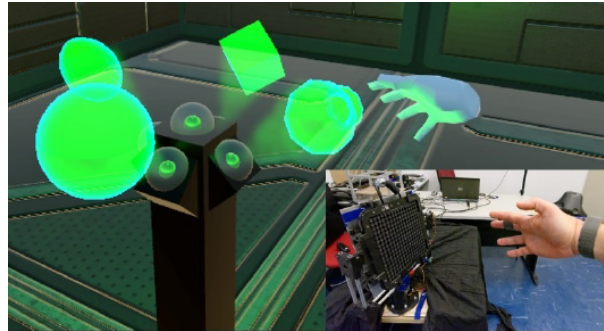


Figure 1.17 – The mid-air haptic display presented by Howard et al. [51]. This device is capable of rendering haptic feedback with a pan-tilt mounting that rotates an ultrasound mid-air haptic shape display.

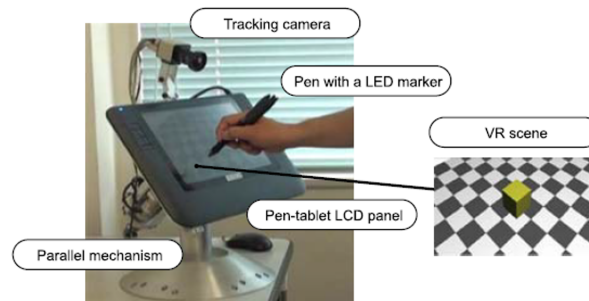


Figure 1.18 – The actuated surface display presented by Takagi et al. [7]. The grounded fixed platform ETHD displaced an actuated surface display that was touched by users using a stylus. The actuated display permitted to render several shapes by applying force against the stylus when the latter touched the display.

render different types of concave and convex surfaces. Other examples of this approach can be found in the work of [27], [35], [46], [48]–[50].

Fluid-based Surface Displays This type of surface display comprises diverse methods that have been used as haptic displays such as magnetic fluids presented by Tsujita et al. [42], [52]. This magnetic fluid could simulate tissue that can be used for a surgical simulation with the same tools of a physician. The perceived "density" of the fluid could be controlled by a system that changed the electrical current passing through the fluid. Pneumatic devices have also been considered for dynamic surface rendering for ETHDs [53], [55]. The work of Boem et al. [53] used a series of inflatables for creating a novel musical instrument. The inflatable surface display proposed by Takizawa et al. [55] aimed to recreate complex shapes such as organs for medical applications.

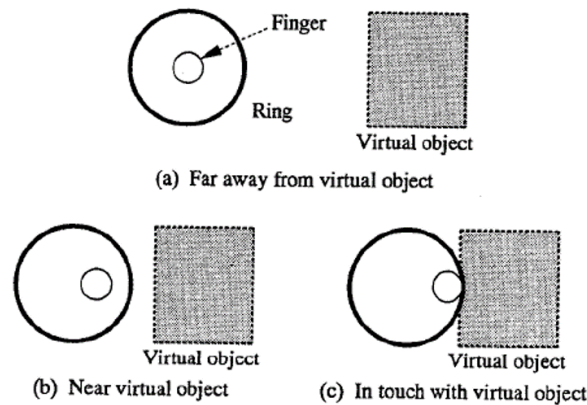


Figure 1.19 – The ring/thimble principle presented by Yoshikawa et al. [46]. This research work uses a principle for haptic rendering based on having a surface around the users’ finger without having any contact with it until users desire to engage contact with a surface in the VE.

Rotatory Surface Displays This type of surface display intends to exploit the shape properties of curved surfaces and translating actuators to provide users the sensation of touching larger surfaces due to a virtual coupling of the users’ hand position as well as the surface display position and rotation. This approach has been considered before in haptics as seen in the works of [66], [67] and later brought in to the ETHD field [8], [19]. An example of this rotatory surface display can be seen in Figure 1.21.

Locomotion Platforms This type of surface display permits to render a walking environment where users can step on. The ETHD research works that consider this approach come from Iwata’s team [28], [37] as they represent haptic feedback directed to the users’ feet.

1.4.3 Tracking Systems

ETHDs require a tracking device that provides information of the spatial location of users’ hands, arms, and overall bodies. These devices have been changing accordingly with technological evolution. Three different categories for tracking devices for ETHDs can be found:

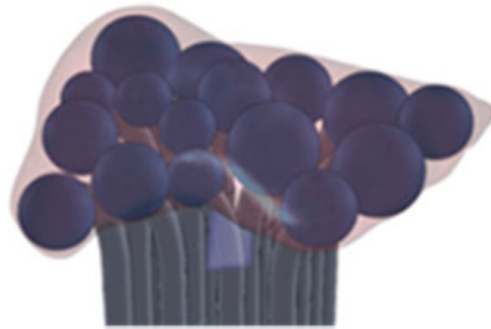


Figure 1.20 – The fluid-based shape display presented by Takizawa et al. [55]. The surface display presented in this research work was conceived to recreate different types of body tissues and organs that could serve for medical applications.

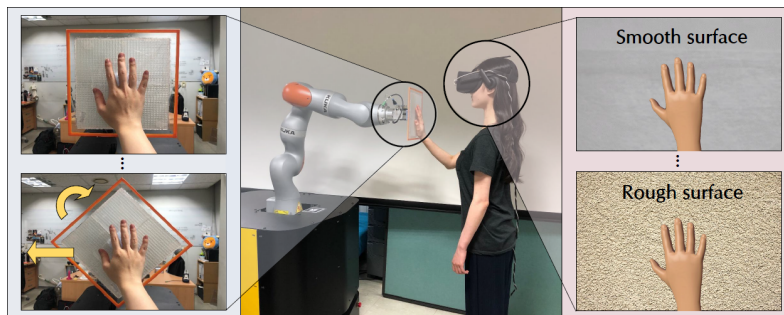


Figure 1.21 – The rotatory surface display presented by Kim et al. [8]. The surface display in this research work generated different textures by spinning under different velocities when the users’ touched the rotatory surface. The different velocities generated different types of friction under the user’s finger and thus it produced several textures as reported by this study.

1.4.3.1 Built-In Tracking System

Some ETHDs do not have an external tracking system since they depend on embedded sensors on the actuators that can provide tracking information such as [21], [23], [34], [44], [45], [55], [57]. In the case of ring/thimble shape displays [27], [35], [36], [46], [48]–[50], the sensors are located inside the thimble and thus the user finger position can be extracted for placing the haptic feedback in the desired position. An example of this tracking system can be seen in Figure 1.23.

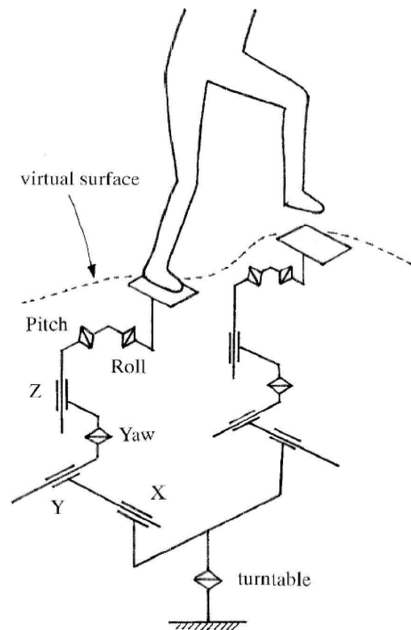


Figure 1.22 – The locomotion platform presented by Iwata et al. [37]. This device placed a surface to be stepped on when users walked in a simulation in VR.

1.4.3.2 Marker-based Tracking System

This type of tracking system relies on markers that can be located at the users' hands that are later spatially located by a device setup around an interactive scenario as we can see in [1]–[3], [14], [19], [37]–[43], [51], [52], [59]. An example of this approach can be seen in the work of Howard et al. [51]. In the case of ungrounded ETHDs, the devices are also spatially located for the system to acknowledge their position during the simulation [4], [5], [9], [10], [15], [22], [24], [28], [29], [31]–[33], [60].

1.4.3.3 Marker-Independent Tracking System

This type of tracking system does not depend directly on a marker mounted onto the users to provide spatial information. Frequently, this type of devices relies on infrared technologies along with sophisticated computer vision to detect users' bodies and other objects in an interactive scenario as seen in the works of [6]–[8], [20], [26], [30], [44], [47], [54], [56]. For instance, the work of Kim et al. [26] used a RGBD sensor to track users head and hand positions (see Figure 1.25).

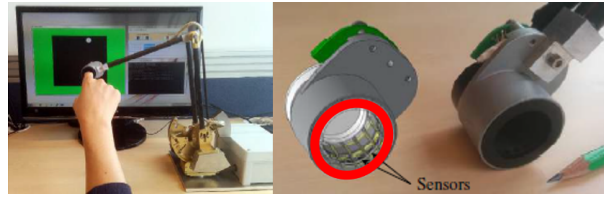


Figure 1.23 – Built-in tracking system presented by Gonzalez et al. [48] (Highlighted in red). The proposed ETHD used a built-in tracking system inside their ring surface display as a tool to track the users' finger in their system.



Figure 1.24 – Marker-based tracking system presented by Howard et al. [51] (Highlighted in red). The proposed ETHD used a Vive Tracker as a tool to track the users' hand in their system.

1.4.4 Visual Display Devices

Ever since their conception, ETHDs have used VEs to conceal the robotic system that displaces the contact area [12], [13], [27]. This can be done through virtual, augmented (AR) or mixed reality (MR). A description of the visual display devices used in ETHDs is presented below. More details about the virtual environments displayed in these devices can be found in Sections 1.6 and 1.7.

1.4.4.1 Screens

Researchers have used screens to conceal the haptic displays by displaying virtual imagery in front of the user. This approach relies on AR technology by mixing elements of real-life scenarios with the virtual elements of the tasks being carried by users. Screens in ETHD literature have also served to display visual [6] and haptic feedback [41] for remote palpation. Screens have also been used in ETHD systems designed for surgical

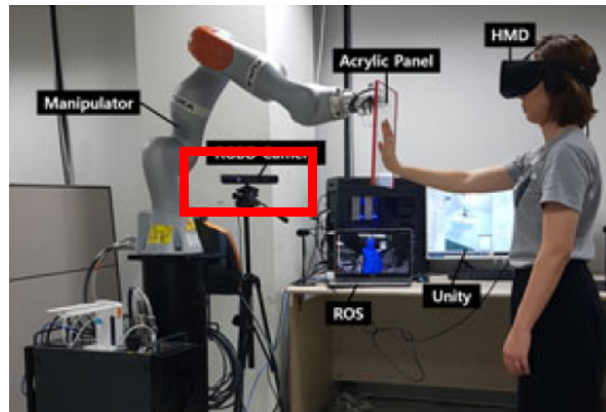


Figure 1.25 – Marker-Independent tracking system presented by Kim et al. [26] (Highlighted in red). The proposed ETHD used a Microsoft Kinect as a tool to track the users' body in their system.

training [42], [52]. Screens can also be the means to transmit haptic feedback, such as the case of Takagi et al. LCD pen tablet display [7]. Literature also reports the use of a screen to receive a projection of a VE in front of the user as a means to contextualize the task such as the case of the juggling VE of Ruffaldi et al. [40] (see Figure 1.26). Screens have served as an alternative to an immersive display such as an HMD in research works that are mostly focused on surface rendering rather than a full integration of the ETHD system with a VE [35], [36], [46], [48], [49]. In early research works the ETHD concept is presented considering the use of an HMD whereas the prototype actually used a screen [1], [14], [34].

1.4.4.2 Virtual Reality Head-Mounted Display

Most of the ETHDs reported in this review use VR-based HMDs to display a VE [2], [3], [19], [20], [22], [25], [26], [28]–[32], [37], [43]–[45], [47], [51], [53]–[56], [59], [60]. This approach is one of the most frequently used since it permits to fully conceal the real environment around the user and place virtual elements related to the task being carried by the user (see Figure 1.27). VR-based HMDs become more useful when the haptic stimuli comes from multiple sides around the user such as the case of the Haptic-Go-Round device by Huang et al [4] (see Figure 1.41) or in the cases of Ungrounded UAV ETHDs such as: [5], [9], [10], [15], [24], [33].



Figure 1.26 – Screen display used in the ETHD system by Ruffaldi et al. [40]. The proposed ETHD used an stereoscopic projection over a screen to display the juggling balls that were rendered by their system for the task of virtual juggling in a VE.

1.4.4.3 Augmented and Mixed Reality Head-Mounted Displays

There is a case where an AR-based HMD was used in the research of Jeon [38] and a recent case where an MR HMD was used in the research of Aygün et al. [39]. These systems partially occlude the devices' shape display to couple the virtual objects with their physical counterpart thus giving rendering haptic feedback that matched the virtual surface's properties.

1.5 Haptic Feedback Related to ETHD Interaction

This section discusses perception that can be obtained through haptic feedback given by ETHDs. The first subsection discusses the two types of haptic sensory information present in ETHD research: tactile and kinesthetic. The second subsection explains the different types of haptic surface exploration that have been used through the reviewed ETHDs.

1.5.1 Haptic Sensory Information Provided by ETHDs

In literature, there are two different types of human haptic perception: kinesthetic and tactile [69] and both of them are involved in ETHDs. A detailed explanation is presented hereby:

Authors	Year	Actuator Sub-type	Surface Display Sub-type	Tracking System	Visual Display	Application
McNeely et al. [12] (theoretical)	1993	Robotic Arm	Button/Switch	Theoretical	VR HMD	Research
Hirota & Hirose [27]	1993	Robotic Arm	Ring/Thimble	Built-In	N/I	Research
Tachi et al. [13] (theoretical)	1994	Robotic Arm	Button/Switch	Theoretical	VR HMD	Research
Yokokohji et al. [1]	1996	Robotic Arm	Flat Surface	Marker-based	Screen	Research
Yoshikawa et al. [46]	1997	Robotic Arm	Ring/Thimble	Built-in	Screen	Research
Inoue et al. [45]	2000	Robotic Arm	Button/Switch	Built-in	VR HMD	Industry
Iwata et al. [37]	2001	Fixed Platform	Locomotion Platform	Marker-based	VR HMD	Research
Yokokohji et al. [14]	2001	Robotic Arm	Button/Switch	Marker-based	Screen	Research
Cini et al. [50]	2005	Robotic Arm	Ring/Thimble	Built-in	N/I	Research
Iwata et al. [28]	2005	Mobile Platform	Locomotion Platform	Marker-based	VR HMD	Research
Provancher et al. [35]	2005	Robotic Arm	Ring/Thimble	Built-in	Screen	Research
Yokokohji et al. [34]	2005	Robotic Arm	Actuated Surface	Built-in	Screen	Research
Nakagawara et al. [23]	2005	Wearable	Actuated Surface	Built-in	None	Industry
Drif et al. [21]	2008	Fixed Platform	Vibratory Surface	Built-in	N/I	Research
Kuchenbecker et al. [36]	2008	Robotic Arm	Ring/Thimble	Built-in	Screen	Research
Ruffaldi et al. [40]	2011	Robotic Arm	Volume	Marker-based	Screen	Entertainment
Yafune & Yokokohji [25]	2011	Robotic Arm	Button/Switch	Theoretical	VR HMD	Industry
Tsujita et al. [42]	2013	Fixed Platform	Fluid-based	Marker-based	Screen	Medicine
Takagi et al. [7]	2013	Fixed Platform	Actuated Surface	Marker-Independent	Screen	Research
Nishimura et al. [57]	2014	Wearable	Actuated Surface	Built-in	N/I	Research
Portoles et al. [41]	2014	Fixed Platform	Actuated Surface	Marker-based	Screen	Medicine
Filippeschi et al. [6]	2015	Robotic Arm	Actuated Surface	Marker-Independent	Screen	Medicine
Gonzalez et al. [48]	2015	Robotic Arm	Ring/Thimble	Built-in	Screen	Research
Araujo et al. [20]	2016	Robotic Arm	Flat Surface	Marker-Independent	VR HMD	Ind./Entmt.
Jeon [38]	2016	Robotic Arm	Actuated Surface	Marker-based	AR HMD	Research
Lee et al. [56]	2016	Robotic Arm	Button/Switch	Marker-Independent	VR HMD	Industry
Yamaguchi et al. [10]	2016	UAV	Volume	Marker-based	VR HMD	Entertainment
Abdullah et al. [24]	2016	UAV	Flat Surface	Marker-based	VR HMD	Entertainment
De La Cruz Fierro et al. [49]	2017	Robotic Arm	Ring/Thimble	Built-in	Screen	Research
Brice et al. [44]	2017	Robotic Arm	Volume	Built-in	VR HMD	Medicine
Devine et al. [43]	2017	Robotic Arm	Volume	Marker-based	VR HMD	Entertainment
Knierim et al. [33]	2017	UAV	Volume	Marker-based	VR HMD	Entertainment
Siu et al. [29]	2017	Mobile Platform	Pin-Array	Marker-based	VR HMD	Entertainment
Takizawa et al. [55]	2017	Robotic Arm	Fluid-based	Built-in	VR HMD	Medicine
Posselt et al. [2]	2017	Robotic Arm	Flat Surface	Marker-based	VR HMD	Industry
Vonach et al. [47]	2017	Robotic Arm	Flat Surface	Marker-Independent	VR HMD	Entertainment
Boem & Iwata [53]	2018	Robotic Arm	Fluid-based	N/I	VR HMD	Entertainment
Fitzgerald et al. [30]	2018	Mobile Platform	Pin-Array	Marker-Independent	VR HMD	Ind./Entmt.
Hoppe et al. [5]	2018	UAV	Volume	Marker-based	VR HMD	Entertainment
Kim et al. [26]	2018	Robotic Arm	Flat Surface	Marker-Independent	VR HMD	Research
Knierim et al. [9]	2018	UAV	Volume	Marker-based	VR HMD	Research
Tsujita et al. [52]	2018	Fixed Platform	Fluid-based	Marker-based	Screen	Medicine
Yamaguchi et al. [3]	2018	Fixed Platform	Flat Surface	Marker-based	VR HMD	Industry
Abtahi et al. [15]	2019	UAV	Volume	Marker-based	VR HMD	Entertainment
Furumoto et al. [54]	2019	Fixed Platform	Mid-Air Haptics	Marker-Independent	VR HMD	Entertainment
Meguro et al. [19]	2019	Robotic Arm	Rotatory End-Effector	Marker-based	VR HMD	Research
Aygin et al. [39]	2020	Fixed Platform	Volume	Marker-based	MR HMD	Research
Bouzbib et al. [59]	2020	Mobile Platform	Volume	Marker-based	VR HMD	Entertainment
De Tinguy et al. [22]	2020	Wearable	Volume	Marker-based	VR HMD	Entertainment
Gonzalez et al. [31]	2020	Mobile Platform	Volume	Marker-based	VR HMD	Research
Howard et al. [51]	2020	Fixed Platform	Mid-Air	Marker-based	VR HMD	Research
Huang et al. [4]	2020	Fixed Platform	Volume	Marker-based	VR HMD	Entertainment
Kim et al. [8]	2020	Robotic Arm	Rotatory End-Effector	Marker-Independent	VR HMD	Research
Kovacs et al. [60]	2020	Wearable	Volume	Marker-based	VR HMD	Entertainment
Suzuki et al. [32]	2020	Mobile Platform	Volume	Marker-based	VR HMD	Research

Table 1.1 – Summary table containing all the works analyzed through this review. The table displays all the hardware details of the reviewed papers as well as the applications of these research works. N/I stands for no information found.



Figure 1.27 – VR-based HMD used in the ETHD system by Brice et al. [44]. The proposed ETHD used an HTC Vive VR-based HMD as a tool to display the VE that contextualized the haptic feedback coming from the occluded haptic display.

Tactile Perception Tactile perception is related to the identification of surface properties such as texture, shape, mass and sponginess of objects [69]. Texture perception has been achieved by the ETHD field by using multi-textured [2], [20] and rotatory end-effectors [8], [19]. In the case of the rotatory end-effectors, researchers suggests that perceived friction might also help for increasing the range of perceived textures [8], [19], [66], [67]. Tactile perception is also present in both ETHD’s surface display types. In the case of dynamic shape displays, pin-arrays permit to render a large variety of shapes due to their re-configurable pins [29], [30]. Other approaches consist of fluid-based end-effectors that can render different volumes to be explored [42], [53], [55], actuated surfaces that can level up against the fingers to render an specific shape [21], [23], and ring/thimble end-effectors that turn and press around the users’ finger to render different shapes as [35], [36], [46], [48], [50]. Static shape displays comprise the classic approach of providing a tangible object to be touched by the user as seen in [1], [20], [26], [31], [32], [44], [47]. Object mass perception has been explored in the the work of ungrounded ETHDs in the case of UAVs that permit to be held by users [15], [24] and to enclose objects and fully grasp objects that could be thrown as seen in [22].

Kinesthetic Perception Kinesthetic perception is oriented towards providing sensations related to limb movement and position [69]. This type of perception is not as frequent as the former since most ETHDs are designed for simple contact with a surface. Dynamic surface displays [7], [21], [29], [30], [34], [42], [53], [55], [62] influence users’ kinesthetic

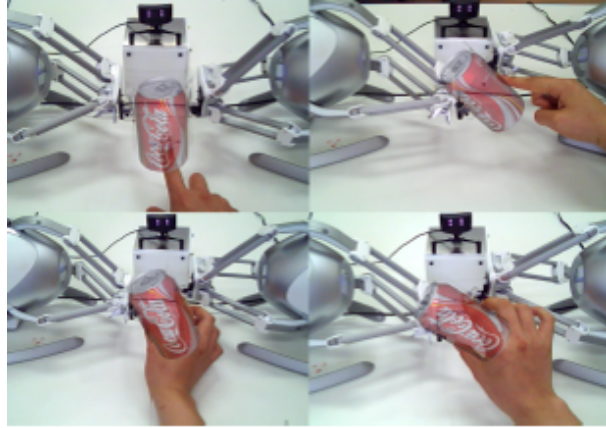


Figure 1.28 – AR-based display used in the ETHD system by Jeon [68]. The proposed ETHD used a Vuzix Corporation WRAP1200 AR-based HMD as a tool to display the objects that could be rendered with a plate displaced by two Novint Falcon haptic displays.

perception since they elicit complex limb movements. Concerning hardware types, UAV ETHDs have explored kinesthetic perception such as the work of Abdullah et al. which uses a UAV’s capability for moving towards the opposite direction where the user is applying a force. Users held the UAV with a handle attached to the latter. The drone pushed itself downwards, thus achieving a force of 2.97 N. Research’s authors commented that the forces achieved by the drone are similar to those rendered by conventional haptic devices [24]. In addition, Yamaguchi et al. developed a haptic display using a UAV for a VR simulation directed to render a stiffness sensation. The drone used a piece of paper hung on one of its sides. This allowed the paper to receive force from the airflow produced by the drone. Users had to use a grabbing device to touch a paper so that they could feel force feedback [10]. Grounded ETHDs have also used kinesthetic feedback as in [6], [26], [39].

1.5.2 Haptic Exploration

In this subsection, we discuss the different haptic exploratory procedures that can be present in an ETHD system. First, the classical contact procedure provided by most ETHD systems is discussed. Later, more complex procedures are discussed. Table 1.2 displays a classification of the reviewed ETHDs according to the haptic exploration used in those systems.

1.5.2.1 Contact

Contact refers to simple hand contact with the shape display held by the ETHD surface display. This type of exploration is the most used in ETHD literature since it only involves touching a part of an object integrated in a working environment and it exclusively involves tactile haptic feedback. Examples of this approach can be found in all ETHD hardware such as: grounded robotic arms [1], [12]–[14], [19], [20], [25]–[27], [34]–[36], [43]–[49], [54], [70], fixed platform [21], [51], ungrounded UAV [5], [9], [15], [24], [33], mobile platform [29]–[32], [59] and wearable [23], [57]. In the particular case of ETHDs designed as locomotion platforms (the research work of Iwata et al. [28], [37]), we decided to consider as contact the action of stepping over the devices’ surface display.

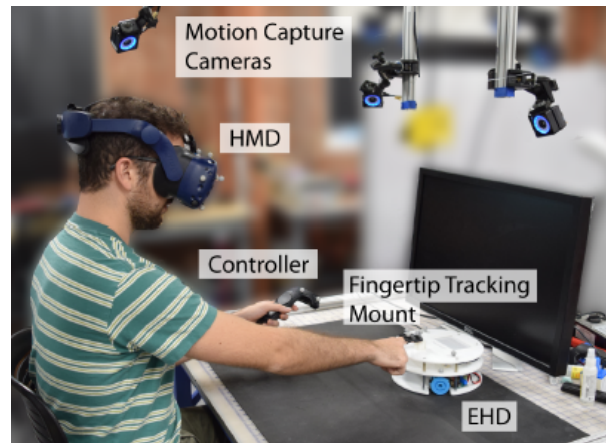


Figure 1.29 – Mobile Platform ETHD proposed by Gonzalez et al. [31]. This research work allows contact with a surface display that is displaced by a tabletop wheeled device.

1.5.2.2 Haptic Exploratory Procedures

ETHDs are not limited to providing sensations related to contact. This review takes into account more complex procedures for exploring rendered shapes according to the classification made by Lederman & Klatzky [71], there are different types of haptic exploratory procedures (EPs). These procedures were determined by the usual hand movements executed during haptic interaction. These EPs are the following: lateral motion, pressure, static contact, unsupported holding, enclosure, contour following, part motion test and function testing. A description of the aforementioned EPs in ETHD research is presented below.

Lateral Motion Lateral motion refers to sideways movement in the encounter between hand and object [71]. The lateral motion EP has been considered as an EP for texture rendering in the work of [2], [20] using a multi-textured surface display. In these works, the robot places the haptic device and rotates it according to the surface the user needs to touch. Later, the work of Yamaguchi et al. [3] looked for increasing the contact area for a textured surface. Lateral motion is present as well in the work of Meguro et al. [19] and Kim et al. [8] for obtaining friction feedback by rotating their device's surface display. The work of Nishimura et al. [57] provides the sensation of friction and vibration using a 2-DOF mechanism based on a spinning band. The authors present this work as a wearable device that could be reached by the users' fingertips at any given moment.



Figure 1.30 – Lateral motion exploratory procedure presented in the work of Yamaguchi et al. [3]. The device presented in this work allowed users to explore large textured surfaces through hand lateral motion.

Pressure Pressure refers to force application towards an object's surface [71]. ETHDs based on grounded actuators such as [6], [7], [39], [41], [42] are an example of pressure EPs since these efforts primarily rely on hardness for rendering objects weight and volume. Pressure has been used in ETHDs for rendering medical palpations targeting telemedicine [42], [52]. The pressure EP can also be found in fluid-based shape displays [53], [55]. This EP can also be found on ungrounded ETHDs such as the case of Yamaguchi et al. [10] where users felt the pressure of stabbing a virtual enemy.

Contour Following & Enclosure Contour following refers to grab and object and enclosing its contours while enclosure refers to contact an object's contour [71]. Contour following has been considered on ETHDs such as [27], [35], [36], [38], [50] that involved

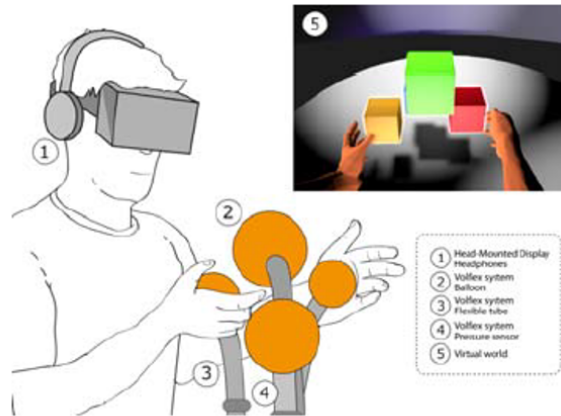


Figure 1.31 – Pressure exploratory procedure presented in the work of Boem et al. [53]. This research work proposes an ETHD using inflatable balloons as shape displays that could be used as a musical instrument within a VE.

hand and finger movement to explore different shapes presented in VEs. Enclosure applied to ETHDs can be found in the work of Abtahi et al. [15] where researchers exploited the properties of an ungrounded UAV-based ETHD for recreating the task of displacing a box in a VE. This EP can be also found in the grasping action in grounded ETHDs [4], [34], [44], [54] and in wearable devices by [22], [60].



Figure 1.32 – Contour following exploratory procedure presented in the work of Gonzalez et al. [48]. This research work profits from the shape display around the users' finger to recreate surfaces that can be explored in a 2D VE. The task in the proposed VE consists of exploring the contour and exterior of 2D shapes.

Static Contact & Unsupported Holding Static contact refers to constant contact between the hand and the object concerning temperature perception [71]. Out of all the presented research in this review, only Araujo et al. [20] have reported the usage of an end-effector capable of providing thermal haptic feedback, thus representing the category of static contact EP. Unsupported holding refers to the action of lifting an object [71]. In this category, ungrounded UAV-based ETHDs are the ones that exploit the feature of not being held by any kind of actuator [15], [24].

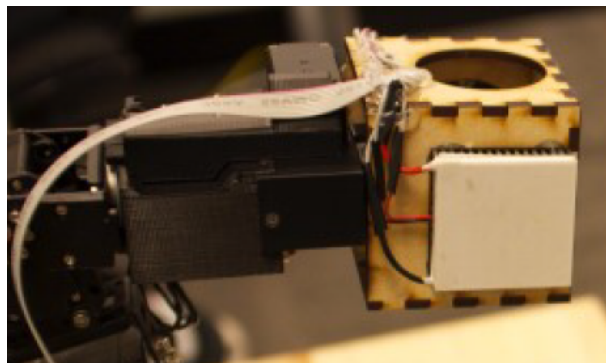


Figure 1.33 – Static contact exploratory procedure presented in the work of Araujo et al. [20]. A device capable of reproducing thermal haptic feedback is presented in this research work. Users are prompted to establish static contact inside this device in order to feel temperature changes with their hands.

Part Motion Test & Function Test Part motion test refers to the action of moving an object's part while function test refers to execute the function on an object [71]. Concerning part this EP, the work of Yafune & Yokokohji [25] present a lever simulation using an ETHD. The work of Lee et al. [70] recreates the task of switch manipulation. The function test EP was introduced into ETHD literature by the works of Inoue et al. [45] and Yokokohji et al. [14]. The former ETHD simulated buttons of airplane cockpit while the latter simulated switches in different positions. Later, the work of Araujo et al. [20] aimed at recreating function testing with a multi-button surface display. The work of Huang et al. uses these two EPs by permitting users to manipulate objects to control a ship [4].

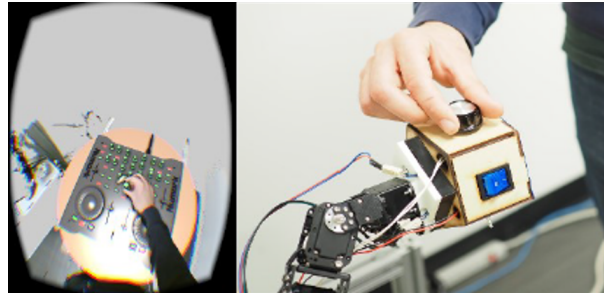


Figure 1.34 – Part motion test exploratory procedure presented in the work of Araujo et al. [20]. This research work presented a multi-sided shape display that contained an assortment of buttons that could be manipulated in a use-case scenario that recreated a virtual disc-jockeying turntable.

1.6 Interaction with ETHDs

This section comprises interaction that is carried within VEs for ETHDs systems. This section is divided in two subsections: (1) the description of the reviewed VEs concerning the tasks that can be carried within and (2) the interaction techniques that address devices' limitations.

1.6.1 Virtual Environment Interaction

Hereby we present several tasks that can be carried out in the reviewed VEs. A classification of the works considering tasks versus actuator types can be seen in Table 1.3.

1.6.1.1 Surface Exploration

Surface Exploration has been present in ETHDs ever since the first iteration by Yokokohji et al. [1] where users could touch the side of a tangible virtual object which was displayed on a screen. The user's hand was superposed using a chroma effect to later be displayed in an AR simulation. Some ETHDs propose VEs where users can explore surfaces that are actively rendered under the user's hand giving the sensation of touching a large surface using shape displays such as pin-arrays [29], [30], ring/thimble end-effectors [35], [36], [46], [48], [49], actuated surfaces [21], [23], [57] and rotating end-effectors [19]. Other approaches consist of exclusively placing the object in an encounter position using dynamic shape displays such as fluid-based end-effectors [53] and mid-air haptics [51]. Surface exploration has also been considered within static shape displays

Actuator/ Haptic Exploratory Procedure	Actuator Subtype	Contact	Lateral Motion	Pressure	Contour Following	Enclosure	Static Contact	Unsupported Holding	Part Motion Test	Function Test
Grounded	Robotic Arm	[26], [47], [70] [19], [20], [43] [25], [34], [44] [1], [12]–[14], [27], [45] [35], [36], [46] [48], [49], [54]	[2], [20] [19] [8]	[53], [55] [6]	[36], [50] [27], [35] [38]	[34], [44]	[20]	-	[25], [56]	[20], [45] [14]
	Fixed Platform	[21], [51][37]*	[3]	[41], [42] [7], [52] [39]	-	[4], [54]	-	-	[4]	[4]
Ungrounded	UAV	[5], [9], [24], [33] [15]	-	[10]	-	[15]	-	[15], [24]	-	-
	Mobile Platform	[28]*[29], [30] [31], [32], [59]	-	-	-	-	-	-	-	-
	Wearable	[23], [57]	[57]	-	-	[22], [60]	-	-	-	-

Table 1.2 – Haptic exploratory procedures for the ETHDs types displays found literature. The classification is based on the haptic exploratory procedures introduced by Lederman & Klatzky [71]. * These research works render haptic feedback directly to the users’ feet as locomotion platforms.

using volumes [5], [9], [14], [20], [31]–[33], [43], [54], [55], flat surfaces [1], [2], [20], [26], [59] or buttons/switches [56].

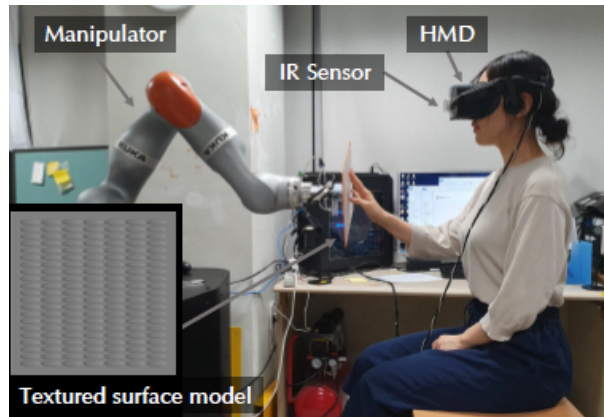


Figure 1.35 – Grounded robotic arm ETHD presented by Kim et al. [8]. This device was designed mainly for surface exploration.

1.6.1.2 Object Manipulation

Object manipulation in VEs for ETHDs was introduced by Yokokohji et al. [34], where they conceived a prototype VE displaying a virtual hand that could grab a virtual object. Later, Ruffaldi et al. [40] designed a VE that contextualized a juggling task in which

the users could manipulate and enclose two spheres that represented juggling ball is in an environment displayed in a screen in front of the user. Object manipulation was later exploited by ungrounded UAV-based [5], [9], [10], [15], [24], mobile platforms [30], wearable ETHDs [22], [23], [60], grounded robotic arms [34], [44], and recently by fixed platforms [4], [39], [53], [54].



Figure 1.36 – Ungrounded wearable platform ETHD presented by Kovacs et al. [60]. This device was designed mainly for object manipulation.

1.6.1.3 Teleoperation

The original ETHD research works envisioned the possibility of using this type of haptic displays primarily for teleoperation by recreating control boards [12], [13], [27]. One of the first interactions comes from Nakagawara et al. [23]. This vision started to be reached when interaction with VEs became more complex at the beginning of the 2010's decade. For this task category, we collected research work that explicitly mentions that their VEs were designed for recreating a task in a real-life scenario that could be operated remotely. Yafune and Yokokohji developed a VE for contextualizing the task of turning switches on and off [25]. The VE consisted on a virtual console displayed in a VR HMD. VEs dedicated to part function interaction tasks have contextualized approaches in ETHDs mostly related to industry [14], [45], [56] and medicine [6], [41], [42], [52] (see Section 1.7). One example is the work of Filippeschi et al. [6] in which they used an AR-based VE displayed on a screen where users could remotely palpate a patient's body with the help of their proposed robotic arm ETHD.



Figure 1.37 – Grounded robotic arm ETHD presented by Lee et al. [70]. This device was designed mainly for teleoperation.

1.6.1.4 Locomotion

Locomotion using ETHDs has been explored since these device's early days under the works of Iwata et al. [28], [37] by creating a particular type of ETHD device that provides contact with users' feet to simulate a large area for walking in a VE. The concept of walking in a VE combined with an ETHD was retrieved by Vonach et al. [47] who integrated a locomotion platform to their grounded system and thus gave the illusion of walking in an infinite environment. The work of Bouzbib et al. integrates the possibility of walking in a VE where users would have the possibility of touching elements such as walls [59].



Figure 1.38 – Ungrounded mobile platform ETHD presented by Iwata et al. [28]. This device was designed mainly for locomotion.

1.6.2 Interaction Techniques for ETHDs

Interaction techniques for ETHD can be divided in whether the system can completely represent the object to be touched (complete object representation) or not (partial object representation).

In the case of complete object representation, the interaction techniques frequently consist in depicting the tangible element in a contextualized VE such as the cases of [4], [10]. The work of Brice et al. uses a similar technique by highlighting the volumes that can be touched in their proposed VE [44]. Abtahi et al. [15] proposed technique signals whether users can touch the entirety or a single part of their ungrounded UAV ETHD system.

In the case of partial object representation, the interaction techniques are designed to guide the user in the haptic exploration to signal where and when to touch the surface. In these cases, the system is in charge of rendering the element at the place where the user wants to engage contact with the surface such in the case of [3], [20], [26]. Posselt et al. [2] used a color code to indicate when their grounded joint-based ETHD is displacing its surface display and to indicate when it is safe for users to touch. Partial object representation rendering considers the possibility of displacing the surface display as the user is exploring a large surface. This possibility has been explored in general haptics research work as in the case of [17], [66], [67]. The rotating surface display approach for ETHDs has been considered in recent research [4], [19].

Actuator/ Interaction Tasks	Actuator Subtype	Surface Exploration	Object Manipulation	Teleoperation	Locomotion
Grounded	Robotic Arm	[1], [26], [35], [36], [50], [55], [56] [19], [38], [49], [53], [54] [2], [14], [20], [43], [46], [48]	[20], [34], [40], [44], [53]	[12], [13], [27], [56] [6], [25], [45]	[47]
	Fixed Platform	[3], [21], [51]	[4], [39], [54]	[41], [42], [52]	[37]
Ungrounded	UAV	[5], [9], [33]	[5], [9], [10], [15], [24]	-	-
	Mobile Platform	[29]–[32], [59]	[30], [32]	-	[28], [59]
	Wearable	[57]	[22], [60]	[23]	-

Table 1.3 – Interaction tasks within virtual environments for ETHDs.

1.7 Applications

Through this review, we identified three main categories for classifying the presented research: medicine, industry, entertainment and research. In this classification, we considered exclusively research work that explicitly mentions application scenarios for their ETHD systems as seen in Table 1.5 where the reviewed works are classified based on actuator types and in Table 1.4 where the works are classified based on interaction tasks.

1.7.1 Medicine

Considering the potential that ETHD systems have for teleoperation, some authors have conducted research in ETHDs for telemedicine. In this case, the efforts are related to medical palpation [6], [41] and surgical training [42], [52], [55].

Portoles et al. [41] designed an ETHD for providing haptic feedback in the task of medical palpation. The grounded fixed platform ETHD used a vibratory screen that displayed an homogeneous tissue layer with several hard stiffness nodules distributed randomly. Participants involved in experimentation were asked to palpate through all the haptic skin simulations to identify different stiffness sensations.

Later, Filippeschi et al. [6] contributed with a device that renders the image of patients bodies and obtains a 3D volume to have an object to touch in the simulation. The 3D model of the patients' bodies can be complemented with organs and tissue simulation that can also render abnormalities. Takizawa et al. [55] suggested that their system could also be used as a surgical training device due to the shape display ability to represent organs' volume and shapes. Exploring alternatives for shape displaying, Tsujita et al. [52] designed a grounded fixed platform ETHD holding magneto-rheological fluid for simulating a surgery scenario involving cutting organic tissue. The proposed device included a VR simulation of the procedure and allowed the use of familiar tools related to their procedures (see Figure 1.39).

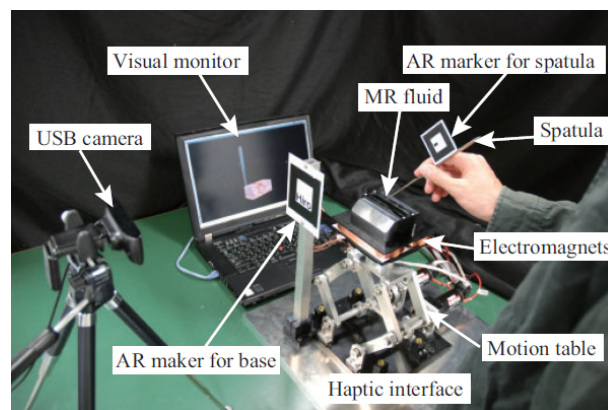


Figure 1.39 – Grounded fixed platform ETHD presented by Tsujita et al. [52]. The ETHD developed by this research group permitted to simulate a surgery scenario using magneto-rheological fluid as the physical counterpart that yielded haptic feedback when users cut through tissue in a virtual simulation.

Brice et al. [44] developed a VE designed to address acrophobia, fear of heights. The

task in this system is to climb a tower by grasping to wood blocks held by a robotic arm ETHD. This approach uses the advantages that a VE can give in the field of phobia treatment.

1.7.2 Industry

ETHDs were first conceptualized as devices that could help in industrial contexts primarily as teleoperation devices [12], [13]. ETHDs have also been conceptualized as part of operational environment simulations since they have the capability of having dynamic shape displays [30], [56]. Work by Yafune & Yokokohji [25] was dedicated to find control algorithms for positioning an ETHD system that could render buttons for interaction. Practical efforts have also been undertaken by the research community, promising applications in the industry. A virtual control panel scenario was created by Araujo et al. [20] using a polyhedral surface display with different types of buttons and switches. Inoue et al. [45] also presented an ETHD device for a virtual cockpit. Nakagawara et al. [23] developed an ETHD that uses a slave hand intended to achieve a task on a remote operation environment for industry. Sato et al. [72] used the aforementioned device along with a GelForce tactile sensor [73] designed to measure magnitude and direction of applied force to develop a haptic teleexistence system.

ETHD researchers have found an opportunity to satisfy fast industrial prototyping and showcasing through multi-textured feedback for surface exploration. Posselt et al. [2] used a multi-textured surface display in order to provide different sensations while touching an automobile interior (see Figure 1.40).

1.7.3 Entertainment

The potential that ETHDs have in the industry of VR-based entertainment has also been explored by researchers particularly for ludic purposes such as video-games [10], music [53], juggling [40] and shape exploration [47]. Concerning more complex activities, Araujo et al. [20] proposed diverse activities such as a fantasy world and a building blocks scenario. In these scenarios, users have the possibility of touching different textures according to elements found the VEs and they could also manipulate objects attached to surface display by disabling the robot's torque. Object manipulation using fixed platforms ETHDs has also been considered in the work of Furumoto et al. [54] and Huang et al. [4]. Other examples of research works for entertainment applications can be seen in [29],



Figure 1.40 – Grounded robotic arm ETHD by Posselt et al. [2]. The VE consists of a recreation of an automobile interior. This research work uses a multi-textured prop attached to a grounded ETHD’s surface display. This configuration permitted to recreate the different textures available to touch at a virtual car cockpit. This ETHD system was conceived for industry applications related to virtual prototyping.

[30], [44], [59].

Ungrounded ETHDs have been exploited in entertainment applications. The example of wearable ETHDs for entertainment scenarios comes from De Tinguy et al. [22] and Kovacs et al. [60] that presented a VE concerning object manipulation where users could grasp apples from a tree and throw them in a basket.

UAV ETHDs have been used to explore encounters with elements of ludic VEs such as in [5], [10], [15], [33]. In the work of Knierim et al. [33] UAV drones played the role of bumblebees, bricks, wood, and skulls as elements hurled to the user for inducing realism to the game simulation. The interaction with this type of displays can also be more sophisticated such as the work of Abdullah et al. [24] proposed a virtual simulation where the user had the task concerning object manipulation that consists of traversing a surface with a sword.



Figure 1.41 – Grounded fixed platform ETHD presented by Huang et al. [4]. This work presented several ludic scenarios. The scenario depicted in this figure recreated a virtual boat. Users could navigate the boat, go fishing, and shoot cannonballs thanks to the passive props used as tangible elements in their virtual scenario.

1.7.4 Research

Other cited works in this review did not focus on an application scenario and they were classified as pure research works. Early efforts in the ETHD field looked for increasing the haptic rendering capabilities of the surface displays and thus were included in this category [1], [12], [13], [27]. The locomotion platforms of Iwata et al. [28], [37] for instance, were conceived with purpose of providing a surface for the user to step on. Most of the ring/thimble surface displays were also conceived to provide complex surface exploration tasks for ETHDs [35], [36], [46], [48]–[50]. Some other works in the ETHD field seemed to aimed exclusively to increase the haptic rendering capabilities of the end-effectors, examples of this can be seen in graspable ETHDs such as [34], and rotatory surface displays such as [8], [19]. Other examples of surface rendering research can be seen in for different sub-types of actuators such as wearable [57] [32], fixed platforms [7], [21], [31], [39], [51], and robotic arms [38]. Research work has also been focused on improving path planning for ETHD algorithms for grounded [14], [26] and ungrounded [9] actuators.

Interaction Tasks / Applications	Medicine	Industry	Entertainment	Research
Surface Exploration	[55]	[3], [20]	[2], [5], [29], [30], [33], [43], [53], [54]	[19], [35], [36], [48], [49] [7]–[9], [14], [26], [46], [50] [1], [21], [31], [32], [38], [51], [57], [59]
Object Manipulation	[44], [55]	[15], [20], [30]	[5], [10], [20], [30] [4], [15], [22], [24], [54] [4], [40], [53], [60]	[9], [32], [34], [39]
Teleoperation	[6], [41], [42], [52]	[2], [20], [45], [70] [23], [25]	-	[12], [13], [27]
Locomotion	-	-	[47]	[28], [37], [59]

Table 1.4 – Interactions present in ETHD application fields.

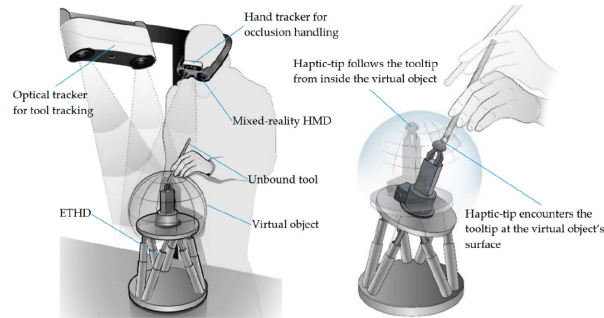


Figure 1.42 – Grounded fixed platform ETHD presented by Aygun et al. [39]. This research work aimed to explore the use of unbound real-life tools that could interact with a surface rendered by their fixed platform actuators in a virtual scenario rendered in a MR HMD.

Actuator	Actuator Subtype / Applications:	Medicine	Industry	Entertainment	Research
Grounded	Robotic Arm	[6], [44], [55]	[2], [20], [25], [45], [70]	[20], [40], [43], [47], [53]	[34]–[36], [38] [8], [19], [26], [46] [1], [12]–[14], [27], [48]–[50]
	Fixed Platform	[41], [42], [52]	[3]	[4], [54]	[7], [21], [37], [39], [51]
Ungrounded	UAV	-	-	[5], [10], [15], [24], [33]	[9]
	Mobile Platform	-	[30]	[29], [30]	[28], [31], [32], [59]
	Wearable	-	[23]	[22], [60]	[57]

Table 1.5 – Actuator types present in ETHD applications

1.8 Discussion

There have been almost three decades since McNeely first conceptualized the idea of an ETHD. The field has evolved in many directions in order to provide intermittent haptic feedback in the most natural way possible. The first years of ETHDs were limited particularly by the actuator type mobility and limited shape display capability [1]. Since robotic arms were the first type of actuators, it might have constrained the evolution of ETHDs due to path planning problems [14], [34], [74]. New approaches to actuators, shape displays, tracking systems and visual displays led to a diversification of these systems as previously discussed in Section 1.3 and depicted in Figure 1.43 and in Table 1.1. ETHDs nowadays not only face the same challenges of the overall haptic research community, they also face challenges related to technological implementations that could help this sector to become more prominent. Current approximations in matters of hardware and interaction techniques are examined and discussed in subsections 1.8.1 and 1.8.2 correspondingly.

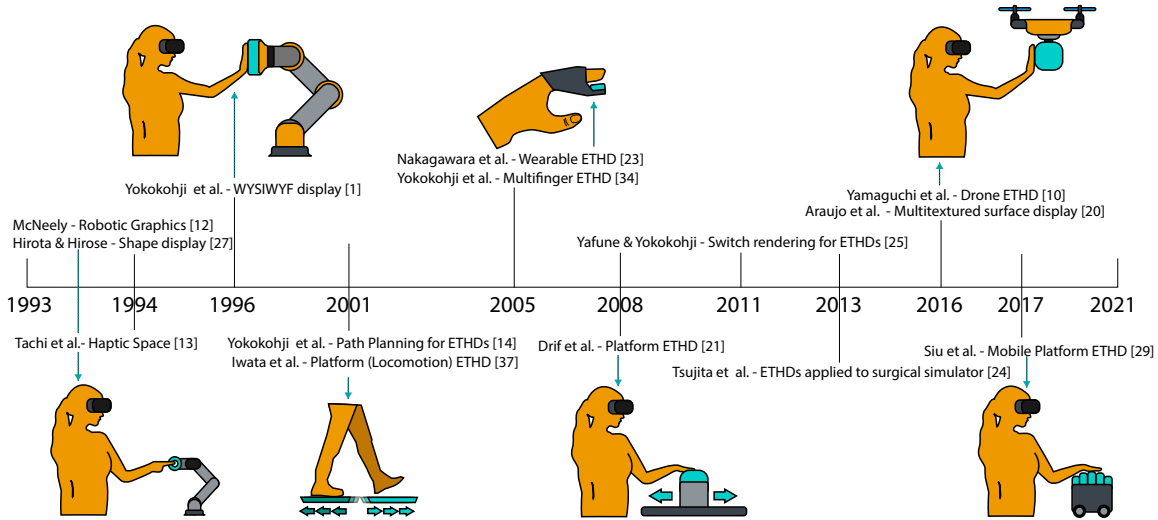


Figure 1.43 – Timeline with highlights over the ETHD research history. This timeline ranges from the proposition of the term "Robotic Graphics" from McNeely [12] to nowadays.

1.8.1 Hardware Approaches for ETHDs

Based on the information provided in these categories, insights about each ETHD actuator type are discussed hereby.

Grounded ETHDs seem to provide a larger variety of haptic feedback due to the capabilities of their actuators as seen in Table 1.2. However, they are limited in terms of mobility since they cannot displace from their origin point, leaving to a limit contact area regardless of the surface display's DOF. By being the first implemented type of ETHDs, researchers have come with many improvements and alternatives to enrich surface display such as curvature rendering in [34]–[36], [38], [50], multi-textured end effectors [2], [20], vibratory [21] and thermal feedback [20]. The application range of this type of ETHD has been widely explored as shown in Table 1.5. Most of the efforts have been used within industrial applications as predicted by McNeely [12] and Tachi [13]. Grounded ETHDs seem to profit from their configuration to render kinesthetic haptic feedback by actively applying force in several directions as seen in [26]. Grounded devices also hold all the applications in the medicine area. Nevertheless, the community suggests that these systems are complex in terms of control [26], [56]. This is mainly due to the fact that research work in grounded ETHDs occasionally uses industrial robotic arms and therefore it is important to conceive algorithms that avoid possible collisions with users while they are interacting with the haptic display [16]. In addition, control algorithms are required

for avoiding collisions with the robotic arms' limbs while displacing the surface display from one position to another [14].

Ungrounded ETHDs provide the flexibility of an "unconstrained" workspace. However, they seem to be limited in matters of rendering kinesthetic haptic feedback unlike their grounded counterparts. In the case of UAVs, they have been signaled by users to be unstable [5] but at the same time, they provide an advantage to rendering lightweight objects. Mobile platform ETHDs [29], [30] are proving to be an ideal alternative to grounded ones. However, the resolution of their shape displays is still a challenge to this research niche [63]. In addition, a challenge for mobile platform ETHDs is the capability of placing their surface display in different heights as it is possible for other actuator types [30]. Applications for these systems seem to be mostly focused on entertainment as seen in Table 1.5. This could be due to their high range of mobility and for their recent appearance which has been joined with the latest generation of HMDs. Wearable ETHDs rely on actuators mounted over the users' hands yet avoid contact with the hand's palm or fingertips. A clear example of this approach is the work of De Tinguy et al. [22]. Haptic feedback consists mainly in contact and enclosure sensations as seen in Table 1.2. While these types of devices might have current technological limitations, more complex actuators such as [57] and [63] are being developed to bring ETHDs an option in portability.

In this review, actuator types were used as the factor for comparing other fields related to ETHDs such as haptic perception and applications. This was done to point out that the current of research presents more types of haptic feedback and applications for grounded actuators. This is due mainly because of the time that grounded devices have been present against ungrounded ones as seen in Figure 1.43. The device hardware classification points out that while grounded devices present a larger variety of haptic exploratory procedures, their workspace is still limited to the size and reachability of their grounded actuators. In contrast, ungrounded ETHDs provide an unconstrained workspace. Nevertheless, the device configuration represents a challenge for incorporating surface displays that could render a wider variety of haptic feedback.

1.8.2 Interaction with ETHDs

Interaction with ETHDs strongly depends on the device's capabilities for rendering haptic feedback. Reported research works addressed their ETHD limitations in matters of workspace, contact area size, and safety through the integration of interaction techniques [2], [15], [22]. Interaction with grounded ETHDs has been reported as more complex since

interaction techniques are needed to guide the users to explore the virtual environment through contact (see Table 1.3). Ungrounded interaction for ETHDs is mostly focused on tangible object manipulations [2], [15], [22] and surface exploration as seen in Table 1.3. Research has stressed that interaction techniques for ETHD systems need to take into account the elapsed time for the system to place the surface display from one position to another while avoiding collisions with users [16]. The work of Abtahi et al. also stressed the importance of integrating visual feedback for user safety into interaction techniques for ETHDs [15].

The performance of an ETHD system is directly related to its application scenario. Based on the reviewed research works, ungrounded ETHDs seem to be adapted for VEs that have more sparse and dynamic objects to be manipulated such as the case of the repositioning of boxes and clothes in the work of Abtahi et al. [15] or in the apple-throwing use-case proposed by De Tinguy et al. [22]. In the case of grounded ETHDs, these systems seem to be adapted for interacting with shape displays adapted for teleoperation (such as surgical simulators and switch rendering) and surface exploration (such as large surface exploration and texture rendering). This can be observed in Tables 1.3 and 1.4.

Recently, other evaluation schemes have been proposed for haptic interfaces and particularly for ETHDs such as the work of Bouzbib et al [75]. In their work, authors propose a method for comparing ETHDs based on factors such as workspace, haptic features, number of props, the possibility of having non-deterministic scenarios, safety, ease of use, etc. The proposed evaluation scheme could be used for determining the advantages of an ETHD over and other dimensions concerning usability, safety, as well as haptic features.

1.9 Conclusion

In this chapter, the existing literature for ETHD research was reviewed. The review's objective was to provide a detailed analysis of the existing hardware, haptic feedback, interaction techniques, and application domains. This chapter presented three main contributions: a definition to the term *Encountered-Type Haptic Display (ETHD)*, a taxonomy to classify the different ETHD actuator types, and an analysis of the research works present in literature.

The definition for ETHDs was based on insights made from literature research works taking into account their main features. This definition could be retrieved as a guide for the haptics research community to properly distinguish ETHDs from other types of haptic

displays.

The taxonomy presented in this chapter was conceived taking into account the main types of robotic actuators reviewed: grounded and ungrounded. The grounded hardware type was subdivided into robotic arm and fixed platform sub-types. The ungrounded hardware type was subdivided into UAV-based, mobile platform, and wearable sub-types.

This chapter also presented an analysis comparing haptic feedback, interaction, and applications for the different actuator types established in the aforementioned taxonomy. The haptic feedback elicited by ETHD literature comprises contact and haptic exploratory procedures, namely: lateral motion, pressure, static contact, unsupported holding, enclosure, contour following, part motion test and function testing [76]. The interactions that can be carried within a VE using an ETHD can be classified into surface exploration, object manipulation, teleoperation, and locomotion. The applications for these devices comprise four domains: industry, entertainment, medicine, and research.

The insights discussed in this literature inspired the challenges and research questions that this thesis addresses. As seen in the thesis' introduction, ETHDs have challenges to address in matters of **usability**, **haptic feedback**, and **actuator performance**. Based on these challenges, seven research questions were conceived: user safety (RQ1), interaction techniques for surface exploration (RQ2), large surface rendering (RQ3), multiple surface rendering (RQ4), object manipulation (RQ5), control algorithm optimization (RQ6), and actuator diversification (RQ7). These research questions will be explored in the following challenges.

IMPROVING USER SAFETY FOR ETHDS

The first thing to ensure when interacting with an ETHD is user safety. This is because users are continuously interacting with a robot that is "hidden" from their view. In this chapter, we propose a set of safety techniques for ETHDs based on visual feedback for helping users to avoid involuntary collisions with these haptic displays. These techniques were created under a design space that considered features related to visual feedback that could remind users about the presence of an ETHD. The iteration of different techniques seeks to propose solutions that balance users' perceived safety without breaking their immersion in the system. A preliminary evaluation was carried out by a set of experts to evaluate the efficiency of the techniques under criteria related to users' immersion and perceived safety.

The main contributions presented in this chapter can be summarized as follows:

- A safety technique design space with a wide generative range of possibilities that could help the ETHD research community to balance safety and immersion according to the purpose and context of the carried task in the VE.
- A set of 18 safety techniques for ETHDs based on visual feedback.
- A set of criteria to evaluate safety techniques for ETHDs based on visual feedback.
- An initial evaluation of the presented safety techniques for ETHDs carried out by a group of experts.

This chapter presents a contribution to ETHDs usability by addressing the research questions related to user safety (RQ1) and interaction technique design (RQ2).

The remaining of this chapter is organized as follows: our design space is introduced in Section 2.1 along with an analysis of the related works. Section 2.2 presents the criteria for evaluating the safety techniques as well as the preliminary evaluation methodology. Results of the safety techniques' performance under these criteria are shown in Section 2.2.4. Section 2.3 discusses the preliminary evaluation results and introduces design guidelines

for creating visual feedback for safety techniques for ETHDs. The chapter ends with a general conclusion.

2.1 Design Space

Designing visual feedback for safety techniques for ETHDs requires balancing users' perceived immersion and safety when interacting with a robotic system in VR. We propose a design space as a tool to iterate several safety techniques for ETHDs based on different visual feedback strategies that inform users about the location, trajectory, and configuration of the ETHD actuators. The design space considers several blocks with features that describe the way the safety techniques could be implemented.

The structure of the design space is presented hereby:

2.1.1 Design Space Organization

The design space is organized in three blocks that describe the feedback given to the user by answering three questions: *what?*, *when?*, and *how?*.

- The **what?** block answers to the question: *what information is the user receiving from the feedback delivered by the safety technique?*
- The **when?** block answers to the question: *when does the feedback is delivered by the safety technique?*
- The **how?** block answers to the question: *how does the feedback is displayed by the safety technique?*

These blocks are further described hereby:

2.1.1.1 Block What

Feedback Information: This design space category refers to the information the user is going to receive as feedback. The two features considered are *warning* and *system state*. *Warning* consists of displaying a warning about a possible collision with a real element in the environment. *System State* consists of providing information about the system state when users get close to the ETHD.

Examples of *warning* are the works of Abathi et al. [15] and Cirio et al. [77] that display an abstract warning for indicating users not to get close to the robot. Some techniques use

visual feedback for describing the *system state* in matters of position, configuration and trajectory. An example in the state of the art is the robot integration in the VE proposed by Vosniakos et al. where users can also acknowledge the robot's actions in the VE [78] (See Table 2.1).

2.1.1.2 Block When

This block comprises the *feedback persistence* category which is described hereby:

Feedback Persistence: This category refers to the duration and the way feedback appears in the VE. The feedback can be displayed only for a moment (sudden), gradually (gradual) or permanently (permanent). The *gradual* feature consists of gradually making the feedback appear based on a parameter such as the distance between the user and the element being represented. The work of Kang & Han [79] presented a set of visual feedback techniques using a point cloud representing an object that could come in collision with the users. Their work considered a point cloud that could appear suddenly (once), gradually as the users come closer to the object, or permanently.

2.1.1.3 Block How

This block comprises the *protection strategy*, *visual integration*, and *representation*. The categories comprised in this block aim at describing how the safety technique protects the user (*protection strategy*) and integrates itself in the VE (*visual integration* and *representation*). These categories are described hereby:

Protection Strategy: This category refers to how the feedback protects users. Three different features are considered for this category: *blocking element*, *virtual bounds*, and *information display*. The *blocking element* feature consists in having a virtual element that interposes itself between the user's hand and the haptic display. This allows having a blocking element that could avoid undesired contact with the haptic device. The *virtual bounds* feature consists in having bounds surrounding elements of the VE to avoid any possible collisions between the user and a part of the VE that is still to be rendered or that is occluding the haptic display's virtual position. The *information display* feature consists in displaying information about the real elements that are occluded in the VE. The displayed information could allow the users to acknowledge the position of real elements to avoid any undesired collisions with those elements. In the context of ETHD interaction, *information display* can comprise the robot's position, trajectory and actuator configuration.

An example of a blocking element in the literature comes from the work of Cirio et al. [77]. Their work presents a virtual companion that interposes itself between users and an element that could collide with the users in the real environment. In the case of the *virtual bounds*, the extended grid technique proposed by Lacoche et al. [80] uses bounding for an object/person that could collide with users when interacting in a VE. In the case of *information display* the Area technique proposed by Lacoche et al. [80] presents information about the position of the other person who could collide with the user (See Table 2.1).

Visual Integration: This category refers to the way the information is going to be displayed to the user concerning the visual elements. The two branches considered are information displayed on the *user interface* or as a *virtual element* integrated into the environment. The *user interface* feature consists in displaying an element as if it was part of the system’s user interface. The virtual element feature consists in using or integrating an element into the VE that could serve as visual support or metaphor for displaying information.

The work of Medeiros et al. [81] illustrates an example of the *user interface* feature. This work used visual feedback that overlaid on the system’s UI in the case of their Color Glow and 3DArrow techniques. The *virtual element* feature is represented in the works of Cirio et al. [77] for the magic barrier tape and the virtual companion (See Table 2.1).

Representation: This category refers to the way the techniques can be represented in the VE. Two different features are considered: *realistic* and *metaphorical*. In the *realistic* feature category, the safety elements are represented as realistic as they can be in the VE as in the work of Hartmann et al. [82] where elements of the real environment are inserted as they are captured from images of the real environment. On the other hand, the *metaphorical* feature category refers to feedback representations based on metaphors and/or analogies. In this feature, safety elements are adapted into metaphors to provide more congruence between the task and/or the VE’s context such as the virtual companion proposed by Cirio et al. [77].

Table 2.1 presents all safety techniques identified in the literature according to the different features of our design space.

2.1.2 Safety Techniques

We developed a set of 18 safety techniques. These techniques were largely inspired by previous techniques proposed in the literature and adapted to the context of interaction

Blocks	Block What?		Block When?			Block How?						
Category	Feedback Information		Feedback Persistence			Protection Strategy			Visual Integration		Representation	
Technique/Feature	W	SS	S	G	P	BE	VB	ID	UI	VE	R	M
Revealers												
Full Reveal		○			○			○		○		○
Partial Reveal		○		○				○		○		○
Gradient Reveal		○		○				○		○		○
Magic Light Reveal		○		○				○		○		○
X-Ray		○			○			○		○		○
Hartman et al. [82] Full		○		○				○		○		○
Lacoste et al. (2017) Ghost Avatar [80]		○		○				○		○		○
Kang & Han (2019) SafetyXR (VR-OP) [79]	○			○				○		○		○
Kang & Han (2019) SafetyXR (VR-GP) [79]	○			○				○		○		○
Kang & Han (2019) SafetyXR (VR-CP) [79]	○			○				○		○		○
Trajectory Beams												
Trajectory Beam		○			○			○		○		○
Guhl et al. (2019) [83]		○		○				○		○		○
Loading Trajectory Beam		○			○			○		○		○
Bounds												
Hiding Box		○			○			○		○		○
Trajectory Bounds		○		○				○		○		○
Hartman et al. [82] Grid		○		○				○		○		○
Lacoste et al. (2017) Extended Grid [80]		○		○				○		○		○
Kanamori et al. (2018) [84]		○		○				○		○		○
Vosniakos et al. (2019) [78]		○		○				○		○		○
Device Bounds		○		○				○		○		○
Radar	○			○				○		○		○
Blockers												
Guardian Angel		○		○				○		○		○
Cirio et al. (2012) Virtual Companion [77]		○		○				○		○		○
Shield		○		○				○		○		○
Signals												
Warning	○			○				○		○		○
Arrow		○		○				○		○		○
Cirio et al. (2012) Signs [77]		○		○				○		○		○
Cirio et al. (2012) Magic Barrier [77]		○		○			○			○		○
Medeiros et al. (2021) 3DArrow [81]		○		○				○		○		○
Medeiros et al. (2021) Color Glow [81]		○		○				○		○		○
Abtahi et al. (2019) [15]		○		○				○		○		○
Screen Overlay		○		○				○		○		○
Lacoste et al. (2017) Safe Navigation Space [80]		○		○				○		○		○
Projector		○		○				○		○		○
Timer		○		○				○		○		○

Table 2.1 – Design Space with related research works and the 18 techniques we designed. This table represents the three blocks of the design space along with their respective features. The conceived techniques along with related literature research works represent different combinations of the design space’s features. The features’ names are abbreviated: warning (W), system’s state (SS), sudden (S), gradual (G), permanent (P), blocking element (BE), virtual bounds (VB), information display (ID), user interface (UI), virtual element (VE), realistic (R), and metaphorical (M).

with an ETHD. All the conceived techniques were implemented in a simulation made in Unity where a virtual model of a grounded ETHD based on the Universal Robot's UR5 cobot was used to render different elements of a virtual automobile cockpit. Figure 2.1 depicts the implementation of all the techniques in this VE. The techniques were grouped into 5 groups that represent the techniques' main features. The conceived groups are presented hereby:

Revealers: This group comprises several techniques dedicated to displaying and rendering the haptic device in the VE. The revealers group integrates techniques inspired by the works of [79], [80], [84] that represent a part of the environment or an element close to colliding the users. This information display is made for users to acknowledge the presence of near elements and thus helping users to avoid collisions with the elements.

Several visual feedback strategies are comprised in this group such as revealing the haptic display entirely, gradually or partially. In the *Full Reveal* technique, the haptic display mesh is rendered entirely through the whole simulation. This technique is inspired by the constant point cloud display proposed by Kang & Han [79] and the contour display presented by Kanamori et al. [84]. The difference from the previous research work relies on the fact that our technique displays the device's contour rather than a point cloud. We conceived a technique to gradually display the ETHD (*Gradient Reveal*) in which the robot's virtual mesh transparency is modified accordingly to the distance between the robot and the users' hands. After a certain threshold, the robot's mesh becomes more opaque as the hand gets closer to it. The implementation of this technique is inspired by the gradient point technique proposed by Kang & Han [79]. We considered the option of only displaying the parts of the robot that were the closest to the user for the *Partial Reveal* technique. When the user approaches to the ETHD, the mesh of the closest part activates and gets displayed in the VE. This indicates the user the presence and proximity of the robot without disclosing the entire device and compromising the users' immersion. The implementation of this technique is inspired by the partial rendering of the user virtual representation by Lacoche et al. [80]. Their technique consisted in representing a ghost avatar of another user's HMD as a means to represent the users' positions in a collaborative VE. We also considered the opportunity of revealing the robot under other approaches based on real-life methods for revealing hidden objects such as the *Magic Light Reveal* and *X-Ray* techniques. This first technique consists of a "black" light that emanates from the user's virtual hand model that shows the haptic display's mesh within the light range. The *X-Ray* technique consists of a screen located in the VE that displays

the users' hands and the haptic display. The metaphor was inspired by the use of x-rays in medicine to see through the skin of patients. This technique is conceived to inform the users about the proximity of their hands to the haptic display without displaying a co-located mesh in the VE.

Trajectory Beams: This group comprises the safety techniques that visually represent the haptic device trajectory when the movement is discrete and the trajectory is planned with anticipation. This principle is inspired by the technique proposed by Guhl et al. [83] that consists in displaying the robot's trajectory when in motion.

The *Trajectory Beam* technique consists in displaying the predefined trajectory of the haptic device's end-effector in the VE. This allows users to better acknowledge the space where the haptic interface will travel. The *Loading Trajectory Beam* technique has a similar behavior compared to the previous one. The main difference is that the rendered trajectory shrinks as the haptic display arrives from the starting position to the final one.

Blockers: This group comprises safety techniques that use a blocking virtual element between the user and the haptic device. These techniques use visual feedback that interposes itself between the user and the device to catch the user's attention and to "block" any possible movement that would yield a direct collision with the haptic device.

The *Guardian Angel* technique uses a virtual guardian that places itself between the user's hand and the haptic device. When the user's hand is far from the robot, the guardian enters an "idle" state. In this state, the guardian wanders around the users, out of their visual field. Once the user's hand becomes closer to the device, the guardian "reacts" and appears immediately between the users' hand and a part of the device where contact could have taken place. We conceived a similar technique using more abstract visual feedback called *Shield*. This technique, as its name suggests, consists of a virtual shield that appears between the user's hand and the device. This "shield" permits users to acknowledge they might enter in collision with the haptic device at the moment users enter in proximity with it. Both techniques require detecting the distance from the users' hand to the closest point of the haptic display virtual representation in the VE. Once a proximity threshold has been detected, the blocker element (in these cases: the guardian angel and the shield) will appear in the midpoint between the users' hand and the closest point between the hand and the haptic display mesh. These safety techniques were conceived under the inspiration of the work of Cirio et al. [77] who proposed a virtual companion for helping users to avoid collisions with the walls in a CAVE system.

Signals: This group comprises safety techniques that consist of metaphorical signaling

methods. This group considers the use of basic signs such as arrows or the conventional warning signs used in work environments. The *Arrow* technique consists of an arrow placed at the top of the haptic display's end-effector. This arrow is always visible through the whole simulation and it allows the user to acknowledge the device's end-effector position. This technique is somehow inspired by the 3D Arrow metaphor presented in the work of Medeiros et al. [81]. The *Warning* technique consists of a virtual warning signal that appears right next to the user's hand when the latter is close to the haptic display. This technique is inspired by the work of Abtahi et al. [15] which displays a warning panel when users get close to the ungrounded UAV-based ETHD. We also considered retrieving a warning technique used frequently on gaming contexts such as *Screen Overlay*. This technique consists of a screen overlay that colors the contour of the users' field of view in red whenever their hand gets close to the haptic display. A similar work in the literature is the Color Glow technique presented by Medeiros et al. [81].

We considered another approach for "signaling" the robot's position through a more abstract metaphor. The *Projection* technique consists in projecting in the VE's floor a circle representing a walking user sharing the interaction workspace in the real environment. Projections are made to display the position and area that an element has in the VE so users can avoid collisions with the aforementioned element. This technique is inspired by the safe navigation space technique presented by Lacoche et al. [80] that projects on the floor of the VE the position of another user sharing the same physical workspace in a VR application. The techniques proposed in this group can also indicate other properties of the robot's movement beyond its position. For instance, the *Timer* technique consists of a timer displayed when the robot is moving in a predefined trajectory. The timer indicates the amount of completion of the predefined trajectory thus indicating when the user can interact with a rendered surface by the haptic display.

Bounds: This group comprises safety techniques that use barriers and/or bounds that surround the elements that the user could collide with. These bounds can surround the device, the device trajectory path or the target contact area. The bounds techniques are inspired by the work proposed by Lacoche et al. [80] and in the SteamVR Chaperone [85]. This group comprises techniques that bound the workspace and/or the haptic device as a means to indicate the user that the interaction space is limited or constrained. Examples of this group are: *Hiding Box*, *Trajectory Bounds*, *Device Bounds*, and *Radar*.

In order to add bounds around the device's mesh, we conceived the *Device Bounds* technique. This technique consists of mesh boxes surrounding the haptic display's virtual

model. When the user gets close to these bounds, the mesh will appear to disclose the device configuration as well as its position. We also considered bounding the final position of the ETHD's trajectory. To do so, we designed the *Hiding Box* technique which consists of a box mesh placed on a desired end-effector's final position. As the haptic display arrives at this desired position, the box's mesh starts to fade and reveals the zone that can be explored and touched once the ETHD has reached its target. The possibility of surrounding the device's trajectory was also considered with the *Trajectory Bounds* technique. When users trespass a given proximity threshold to any point of the trajectory, the mesh surrounding the entire trajectory will appear to indicate that the haptic rendering process is not finished and that the haptic display is displacing its end-effector from one position to another. We conceived a technique that acts as an "inverse" bound called *Radar*. This technique consists of a spinning arrow attached to the users' virtual hand models that act as a compass and radar, indicating the haptic display's position and proximity. The arrow changes color from green to red as the users' hands get closer to the haptic device. The technique's behavior as an inverse bound is justified in the sense that the information displayed by this technique is expected to "bound" the users' hand from any involuntary collision with the ETHD's hidden mesh. The technique is based on radars for detecting objects mainly in military contexts.

2.2 Preliminary Evaluation

A preliminary evaluation procedure was designed for assessing the performance of the safety techniques mainly in the dimensions of users' immersion and perceived safety. First, we defined a set of evaluation criteria from the literature and an interview with experts. These evaluation criteria were then used in a user study to assess qualitatively all the designed safety techniques.

2.2.1 Evaluation Criteria

The proposed criteria were retrieved from insights of the literature on evaluation methods for assessing the performance of their safety techniques and also discussed with experts ($n = 4$) in the ETHD and haptic research fields. Two primary criteria were identified: immersion and perceived safety. In this chapter, we consider *immersion* as the capability that the system (the ETHD and visual display technologies) has to ensure users' immer-

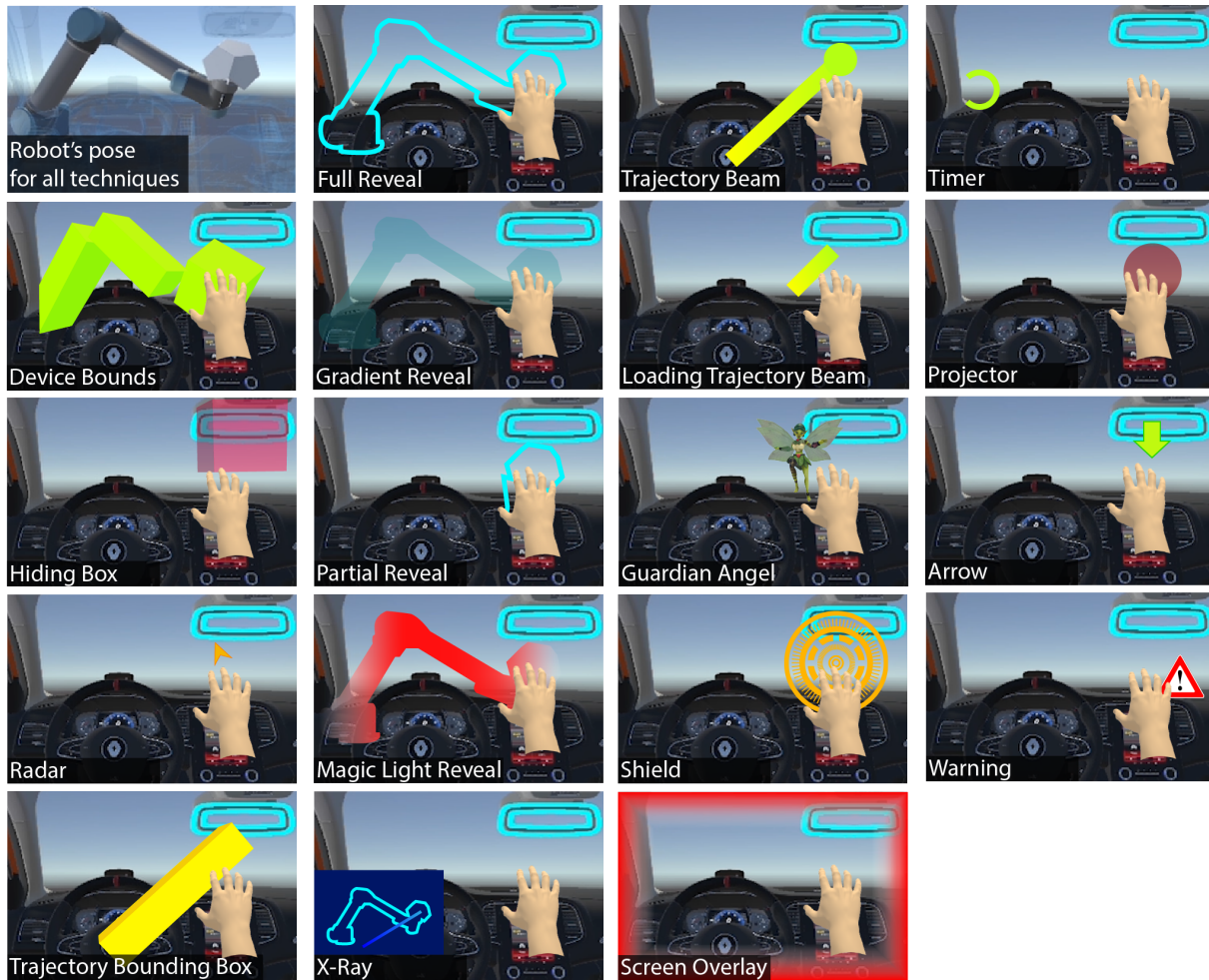


Figure 2.1 – Illustration of the conceived 18 safety techniques designed. The safety techniques are represented in a virtual environment representing an automobile interior. All the technique screenshots represent a status with a robot pose as similar as possible to the robot pose shown on the top left.

sion in the VE by properly rendering sensory feedback without disclosing the presence of real elements behind the scene rendering. Research works such as the works of Kanamori et al. [84] and Hartmann et al. [82] considered immersion as a criterion to evaluate their techniques. In the context of interacting with an ETHD in VR, we considered *perceived safety* as the users' sensation of being safe during their interaction with the haptic display in VR. This criterion has been considered in the literature for assessing if the users feel comfortable when interacting with elements that could come in physical contact with them such as robots [86], [87], walls [82], and other objects present in the workspace [79]. In addition, our literature review and discussion with the experts identified a set of com-

plementary criteria, which could also be linked with immersion and perceived safety.

We first considered other criteria that can be related to properties directly associated to the visual feedback used by safety techniques such as *visual clutter* and *ecological adaptability*. For example, Lacoche et al. [80] assessed the efficiency of the visual feedback proposed by their safety techniques. We considered measuring the visual efficiency of our techniques through cluttering (visual clutter) and aesthetics (ecological adaptability). Visual clutter refers to the degree in which the additional visual feedback occludes the virtual environment. If the visual feedback used within a safety technique clutters the VE, then users' immersion could be compromised since there could be a larger number of distractors when users are performing a task in the VE. Ecological adaptability addresses an aspect of visual feedback more oriented towards aesthetics and pertinence to the context of the VE. We defined ecological adaptability as the visual feedback's adaptability level for being represented in different tasks and contexts in VE. In this context, a safety technique with high ecological adaptability should be able to be implemented using different visual metaphors for a large diversity of contexts and use-case scenarios. On the contrary, a technique with low ecological adaptability might be inefficient under different scenarios and thus it might break users' immersion.

The safety techniques should also be evaluated in matters of their capability of accurately representing information about the presence of the ETHD. We considered the use of *co-location* as an important factor that might help users to acknowledge the presence of the ETHD when they are using an HMD. In the context of visual feedback for safety techniques for ETHDs, co-location refers to the correspondence of the visual feedback to the ETHD's position in the real environment. In the literature, co-location has been considered to display visual feedback about the robot's behavior [88] in an HMD. We considered that safety techniques should also make users aware that they are interacting with a robot in real life. Therefore, we included the feature *device awareness*. This feature refers to how much users are aware of the ETHD's position and state in the VE. Being aware of the actuator's presence is useful for users' perceived safety since they acknowledge the presence of something that can collide with them as signaled in previous research works [79], [82], [86].

We further considered two additional criteria referred as *users' trust* and *mental workload*. In the context of safety techniques, we defined mental workload as the demand imposed on users in the process of understanding the safety techniques. This notion of mental workload is derived from that of Moray et al. [89]. A low mental workload should

be favorable for user safety since users could be easily focused on simple tasks and therefore it could be easier for them to avoid any involuntary collision with the system. Mental workload could also be linked to immersion, as low mental workload could also be linked with less noticeable safety techniques. We considered mental workload based on the study of Kang et al. [79] and Medeiros et al. [81] who assessed users' subjective perception of the attention they invested in doing tasks in VR while avoiding at the same time collisions with elements present in the real environment. Finally, we defined user trust as the level of trust users can have towards the system based on the understanding of the ETHD behavior within the VE. The higher the level of trust in the system, the higher the sense of perceived safety for potential users could be. In the literature, the work of Oyekan et al. [86] evaluated user trust for their studies.

The eight different criteria were assembled in a unique questionnaire with eight items scored with a 7-point Likert scale. For each criterion, the definition was provided to ensure that participants understood well the different concepts. Except for visual clutter and mental workload, higher values means better. For the sake of clarity, the analysis of the results will consider inversed scores ($8 - 1$) for visual clutter and mental workload to ensure that for all criteria higher values mean better.

2.2.2 Participants

Ten participants (2 female, 24-57, $M=34$) took part in the experiment. They were all international experts for an average of 2.8 years spent in the fields of haptics and VR in both academia and industry. Each member of this set of experts has at least one scientific publication in the field of ETHDs and has been involved in a project with ETHDs for more than two years. We used experts instead of non-experts given the form of the experiment.

2.2.3 Experimental Procedure

Due to the current sanitary situation, the experiment was conducted online, requiring participants to visualize videos of each safety technique, and then provide the score for each evaluation criteria. Although it would have been ideal to let participants test the actual ETHD system, we assumed that the experts would be able to imagine the technique in an immersive setting when watching the videos, compared to non-experts. Each technique was presented as a ~ 25 s video showing the ETHD rendering several interest points of an automobile interior, highlighted in blue as presented in Figure 2.1. The videos

displayed two views: (1) a view of the robot moving through the automobile model and (2) the user's view. This allowed participants to see the users' view and, at the same time, the actual movement of the ETHD, to better assess the safety issues by comparing the actual robot configuration in the real workspace to the visual feedback provided by the techniques in the VE. Participants could play the video as many times as they wanted before answering the questions. They were instructed to imagine being in a VR setting with the video showing the technique presented in the VR headset. The participants were then prompted to evaluate on a 7-point Likert scale each one of the criteria discussed in the previous section. Descriptions from the criteria were included for each question to remind the participants about the meaning of each criterion.

2.2.4 Results

During an initial analysis, we explored the role of the principal criteria, immersion and perceived safety (see Figure 2.2). The visual inspection of the data showed one big cluster, with techniques with mean immersion scores between 3.5 and 5.5 and mean perceived safety scores between 3.5 and 4.5. *Full Reveal* and *Gradient Reveal* techniques stood out in the perceived safety score. Although the Friedman ANOVA found significant differences for the perceived safety ($\chi^2(17) = 38.8, p < 0.001$) and immersion scores ($\chi^2(17) = 54.18, p < 0.001$), post-hoc tests (Wilcoxon pairwise with Bonferroni correction) were not significant (all $p > 0.05$). The non-significance of the results can mainly be attributed to the high number of conditions and the correction for multiple pairwise tests.

In a second step, we explored the potential relationships between the primary and the secondary criteria. For this purpose, instead of using cross correlations, we decided to conduct a principal component analysis (see Table 2.2) to extract meaningful relationships among all criteria. Before conducting the PCA analysis, we checked for sampling adequacy using the Kaiser-Meyer-Olkin (KMO) measure. The overall KMO was 0.7, which can be considered as a moderate sampling adequacy. In addition, we used the Bartlett's test of sphericity to observe if the correlations between the criteria were enough for running a PCA ($\chi^2(28) = 160.107; p < 0.001$). Considering the limited sample size, we considered that this was sufficient for a preliminary assessment. When considering only two components, the PCA analysis showed that they could explain 64% of the observed variance and provided a fit of 0.92.

The PCA analysis, see correlation coefficients in Table 2.2, revealed a clear dichotomy of the criteria enabling to split them into two major clusters. The first one considers

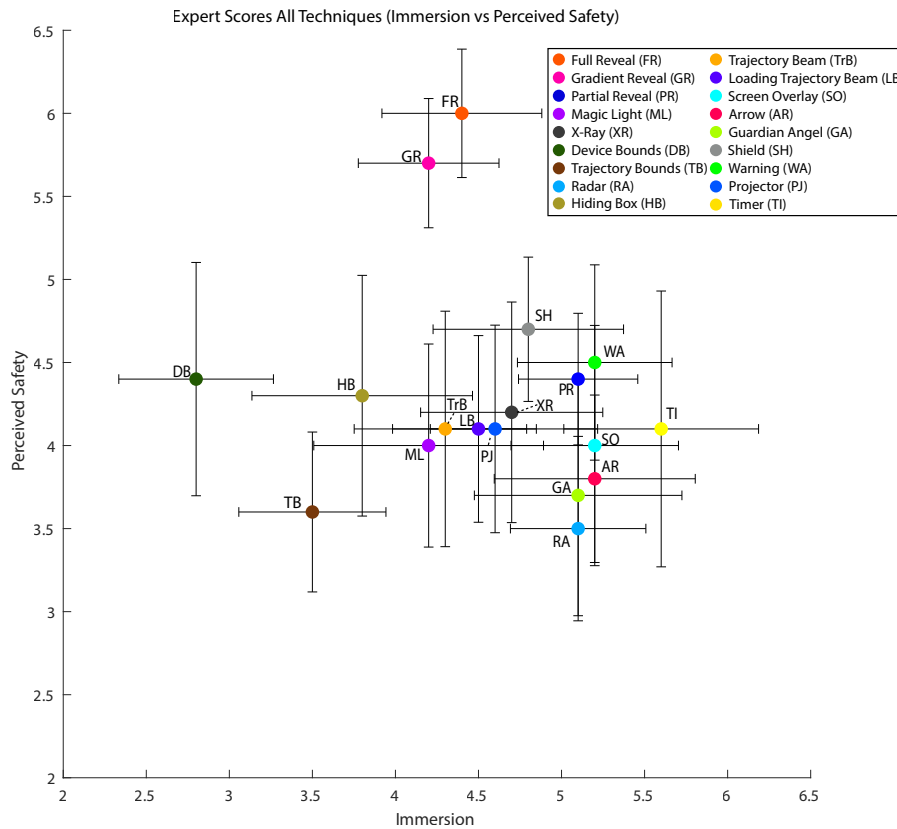


Figure 2.2 – Mean scores (95% CI) for the perceived safety and immersion criteria, for each technique (7-Point Likert Scale). Axes are cropped for clarity.

device awareness, co-location, perceived safety and user trust. The second one considers immersion, visual clutter, ecological adaptability and mental workload. The separation between the two clusters was clear, as the correlation between the unused criteria is weak (smaller or equal than $|0.22|$). Furthermore, the correlations between principal components was low (≈ 0.06). The first cluster aggregates criteria related to the subjective perception and awareness of the robot, while the second cluster focuses more on the impact and adequation of the visual components in the VE. As our main criteria were safety and immersion, and considering that each one was in a different cluster, we decided to name the clusters as "Safety Subscale" and "Immersion Subscale".

We also explored the addition of a third factor, which increased the variance explained to 11% and increased the fit in 0.03. With three factors configuration, the main difference was that the mental workload was strongly correlated with the third component and not the second one. The remaining correlation remained similar. For simplicity and due to the good fit already for two components, we decided to only consider two components.

Criteria	PC1	PC2
Device Awareness	0.86	-0.22
Co-Location	0.85	0.00
Perceived Safety	0.81	0.17
User Trust	0.80	0.12
Immersion	0.06	0.84
Visual Clutter	-0.19	0.80
Ecological Adaptability	0.18	0.65
Mental Workload	0.10	0.60
Eigenvalues	2.86	2.22
Percent of variance	36%	28%
Correlation with PC1	100%	6%
Correlation with PC2	6%	100%

Table 2.2 – The principal component analysis from the questionnaire data. The first part details the correlations for each criterion. The second part presents the eigenvalues and the percent of the variance explained by the principal component. Finally, the third part shows the correlation between principal components.

Table 2.3 presents the average score for each safety technique for each evaluation criterion and the aggregated scores for both subscales. The aggregation was computed by averaging the criteria scores for each cluster. Moreover, Figure 2.2 displays the mean and confidence intervals for each technique with respect to the immersion and safety subscales. The Friedman ANOVA analysis showed a similar result as the one conducted on the immersion and perceived safety criteria, thus we present the results considering the rank among each subscale to provide qualitative results. Regarding the technique clusters, overall, revealer techniques obtained higher scores in the safety-related subscale while presenting average scores in the immersion-related subscale. The trajectory beam techniques obtained average scores in both subscales, while bound techniques tended to obtain the lowest scores in both subscales. For blockers, both techniques obtained average scores, although the guardian angel technique obtained one of the worst scores in the safety subscale. Finally, signal techniques obtained overall the highest scores for the immersion-related subscale, while presenting lower scores for the safety-related subscale. Technique-wise, the *Full Reveal* obtained the highest scores for both subscales, while *Partial Reveal*, *Shield* and *Warning* and *Gradient Reveal* techniques presented a good trade-off between subscales.

Evaluation Criteria/ Safety Techniques	Immersion	Visual Clutter	Ecological Adaptability	Mental Workload	Immersion Subscale	Perceived Safety	Co-Location	Device Awareness	User Trust	Safety Subscale
Revealers										
Full Reveal	4.4	4.2	5.4	5.1	4.8	6	5.6	6.1	5.4	5.8
Gradient Reveal	4.2	3.6	5.3	4.1	4.3	5.7	5.7	6.1	5.4	5.7
Partial Reveal	5.1	5	4.8	4	4.7	4.4	4.5	4.5	4	4.4
Magic Light	4.2	4.3	4.1	3.1	3.9	4	4.5	4.2	4	4.2
X-Ray	4.7	3.5	5.6	3.6	4.4	4.2	3.9	4.1	4.5	4.2
Trajectory Beams										
Trajectory Beam	4.3	3.7	5.2	4.2	4.4	4.1	4.5	3.9	3.8	4.1
Loading Trajectory Beam	4.5	3.9	5.2	4.3	4.5	4.1	4.3	4	4	4.1
Bounds										
Device Bounds	2.8	1.8	4.7	3.6	3.2	4.4	5.1	5.3	3.9	4.7
Hiding Box	3.8	3.2	4.6	5.1	4.2	4.3	3	2.8	3.2	3.3
Trajectory Bounds	3.5	2.8	4.4	3.4	3.5	3.6	3.7	3.5	3.3	3.5
Radar	5.1	5.1	5.1	3.5	4.7	3.5	3.8	3.6	3.6	3.6
Blockers										
Guardian Angel	5.1	4.6	5.6	5	5.1	3.7	3.6	2.5	3.1	3.2
Shield	4.8	3.5	5.4	4.6	4.6	4.7	4.8	3.9	4.2	4.4
Signals										
Projector	4.6	4.2	4.7	3.8	4.3	4.1	4.2	3.6	4.1	4.0
Screen Overlay	5.2	6.1	6.5	4.5	5.6	4	2.3	2.5	3.8	3.2
Warning	5.2	4.8	5.6	4.6	5.1	4.5	4.1	3.8	4.1	4.1
Arrow	5.2	5.9	5.4	5	5.4	3.8	4.2	2.7	4.2	3.7
Timer	5.6	5.9	6.6	4.8	5.7	4.1	3.2	3	4.1	3.6

Table 2.3 – Average response scores for all the techniques and all the evaluation criteria. The three highest values are highlighted in green while the three lowest values are highlighted in red.

2.3 Discussion

This chapter presented a design space for safety techniques for ETHDs based on visual feedback. A total of 18 safety techniques were conceived to explore the different conceptual possibilities from the design space. Some of these techniques were inspired by previous research works. In order to evaluate the safety techniques, we proposed a set of criteria to characterize the techniques concerning immersion and perceived safety (primary criteria), along with six additional criteria corresponding to visual clutter, co-location, ecological adaptability, device awareness, mental workload, and user trust (secondary criteria). In the following, we discuss the scores obtained for each technique, design recommendations for safety techniques and the limitations and future work.

2.3.1 Results Discussion

The analysis of the results showed that there were strong links among the different criteria considered. Two independent clusters of criteria were formed, one aggregating criterion strongly correlated with immersion (Immersion subscale) and another one strongly correlated with perceived safety (Safety subscale). First, although we hypothesized that there would be a trade-off between Immersion and Perceived Safety, both subscales did not

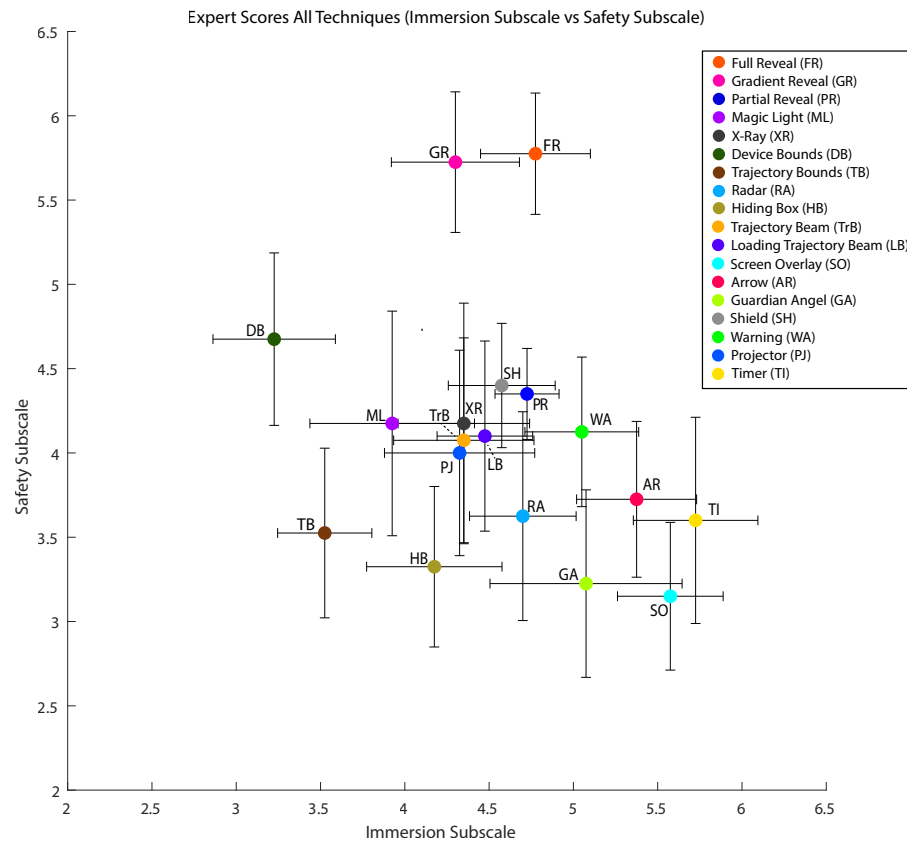


Figure 2.3 – Overall average scores for the Safety (PC1) and Immersion (PC2) subscales, for each technique. Axes are cropped to display values and 95% confidence intervals as clearly as possible.

have a significant correlation (≈ 0.06). From Figure 2.3, we can observe that the majority of the techniques obtained average scores for both subscales. If we observe the techniques obtaining higher scores in the immersion and safety subscale, we can find techniques with higher safety scores but lower immersion scores (e.g. *Device Bounds*) and vice-versa (e.g. *Screen Overlay*). Two outliers can also be found, *Full Reveal* and *Gradient Reveal*, which resulted in the techniques with the highest safety scores. The balance between immersion and perceived safety for *Full Reveal* and *Gradient Reveal* might be because the whole device is being represented and therefore it indicates the device’s configuration and position. However, the fact that the device is being fully shown but in a subtle way had only a moderate impact on immersion according to the experts. We further discuss the results for each individual subscale.

2.3.1.1 Safety Subscale

The safety subscale, in addition to the perceived safety criteria, also included co-location, device awareness and user trust. We can hypothesize that co-location and device awareness increased the knowledge about the robot state, which can be linked with the perceived safety and that user trust was also positively correlated with the perceived safety. The highest scores were obtained by the *Full Reveal* and *Gradient Reveal* techniques that displayed the entire robotic actuator. Both techniques use visual feedback to represent the haptic display as accurately as possible and according to the actuator's configuration and position in the real environment, thus achieving the highest scores in co-location and device awareness. In addition, these two techniques also reported the highest scores for device awareness and user trust. These results are in agreement with results in HRI stating that it is important to disclose the robot's position and configuration when it is integrated in a VE [83]. The *Device Bounds* technique also obtained a high score in the safety subscale, yet, the fact that the representation of the robot was more "clumsy" could have generated a lower perceived safety and user trust. In contrast, the lowest scores were obtained with the techniques that did not display the robot actuator such as the *Screen Overlay*, the *Guardian Angel* or the *Hiding Box*. The only technique that achieved a moderate safety score without displaying the robot actuator was the *Shield* technique, which provided a moderate perceived safety and co-location, but was penalized by a lower device awareness and user trust.

2.3.1.2 Immersion Subscale

The immersion subscale, in addition to the immersion criterion, also included visual clutter, ecological adaptability and mental workload. We can hypothesize that subtle techniques (low visual clutter), and techniques that can be seamlessly integrated with the VE (high ecological adaptability) have a smaller negative impact on user's immersion. Finally, we expect that mental workload would be more correlated with safety, yet this was not the case. This suggests that techniques that were easier to interpret had a lower impact on immersion. The techniques achieving the highest scores were mainly techniques in the Signals cluster, in particular *Timer*, *Arrow* and *Screen Overlay*. These three techniques subtly displayed information regarding the robot, thus obtaining the highest scores in immersion and visual clutter. In addition, as the feedback was subtle they also obtained high scores in ecological adaptability.

In contrast, the techniques that were ranked lower on immersion were those that used bounds around the device (*Device Bounds*), its trajectory (*Trajectory Bounds*) and its final position (*Hiding Box*). The evaluation results suggest that these techniques also ranked high on visual clutter as it can be seen in Figure 2.1. These techniques, when active, display large and colorful mesh boxes that highly contrast with the VE used as a use-case scenario.

Concerning mental workload, the *Magic Light Reveal* technique reported the lowest score. This might be because users needed to place their hand in a position close to the robot but also in an angle that permitted to "reveal" the robot's mesh. Paying attention to those factors while "avoiding" a collision with something that cannot be directly seen in the VE could be highly demanding for users' mental workload. In contrast, the *Full Reveal* technique yielded one of the highest scores for the aforementioned feature since the information of the haptic display is always shown in the VE and thus, it is easier to understand what is happening in the real environment.

2.3.2 Design Recommendations

From the preliminary results on the immersion and safety subscales, several design recommendations could be provided regarding the potential application requirements. For applications focusing on safety, safety techniques that display the entirety of the ETHD's, such as *Full Reveal* and *Gradient Reveal* seem the best choices. Moreover, both techniques had a moderate impact on the user's immersion. The use of *Device Bounds* although having a high perceived safety score is discouraged as its impact on immersion is too high.

In contrast, for applications focused on immersion, techniques such as *Timer*, *Arrow* and *Screen Overlay* seem the best choices. However, these three techniques obtained relative low scores on safety. Thus, potentially being only usable in a specific context in which users are well aware of the ETHD behavior. With this same rationale, the *Radar* technique could also be considered, but it had a strong negative impact in mental workload, which could be overcome with training.

Other methods also presented some good trade-offs between safety and immersion, although they did not excel in any of them. These techniques were the *Shield*, *Partial Reveal* and *Warning*. We believe that these three methods are worth to be considered in further analysis. Furthermore, particular applications that require displaying the ETHD's trajectory could also consider both *Trajectory Beam* and *Loading Trajectory Beam*. The

scores for these techniques displayed average values for all criteria. Finally, the graphical representation can be considered a key factor for designing the visual feedback. In this work, we considered the use of colors that highly contrasted with the VE since we wanted to design visual elements that could be easily perceived. However, in a real application, the visual feedback's aesthetics should be adapted to the context of the VE. Adapting the visual feedback as much as possible to the context of use could enhance safety and increase immersion. However, designers should be aware that users should perceive the visual feedback and therefore, visual contrast should be considered for alerting users of possible collisions. For example, the *Guardian Angel* low performance in the evaluation might be related to the graphic representation of the blocking element, which contrasted notably with the automobile scenario. A notably similar technique, *Shield* yielded a better perceived safety score. This could be due to the simpler visual representation and metaphor presented on the technique's visual feedback.

2.4 Conclusion

This chapter studied the design of safety techniques based on visual feedback for avoiding collisions when using an ETHD in a VE.

Ensuring user safety when interacting with an ETHD within an immersive VE represents a challenge for designers and researchers, as two key factors need to be balanced to ensure an optimal interaction with the system. On one hand, users' immersion needs to be favored to not disrupt the task and the "realism" the ETHD is providing when rendering haptic feedback. On the other hand, user perceived safety needs to be ensured by providing appropriate information about the system's behavior. This trade-off between immersion and perceived safety needs to be addressed with the design of safety techniques for avoiding involuntary collisions with an ETHD.

A design space was created to be used as a tool to iterate different safety techniques for ETHDs based on visual feedback. The design space was organized into blocks describing what and when the feedback is displayed and how it protects the user. A set of 18 techniques was created using the design space. These techniques were clustered into different groups: blockers, signals, bounds, trajectory bounds, and revealers.

A set of criteria were proposed to do a preliminary evaluation of the safety techniques. The primary criteria that were taken into consideration were immersion and perceived safety. Later, a set of secondary criteria was also considered, including visual clutter, co-

location, ecological adaptability, device awareness, mental workload, and user trust. A group of experts was recruited to assess the proposed techniques under the evaluation criteria.

Results suggest that some techniques from the revealers group, (*Full Reveal* and *Gradient reveal*) could properly balance the trade-off between immersion and perceived safety. Techniques from the signals group tended to be evaluated as more immersive whereas techniques from the bounds group ranked high on perceived safety but low on immersion.

DESIGNING INTERACTION TECHNIQUES FOR SURFACE EXPLORATION WITH ETHDs

This chapter proposes a set of interaction techniques for ETHDs dedicated to surface exploration. The set of techniques was conceived in a design space composed of four main factors that refer to ETHDs control: input, movement control, displacement, and contact. The techniques were mainly designed to enable the user to interact with virtual, flat, and wide surfaces using one finger. The global setup of our system is shown in Figure 3.1. We chose to illustrate our techniques through a use-case scenario with a shape coloring task using an ETHD. This task was chosen since it requires interacting with a large surface in which contact information is crucial. We chose to assess the interaction techniques' performance through a user study with a similar shape coloring task. Both quantitative measurements and subjective questionnaires were used to identify the features that could be taken into account for designing an optimal interaction technique dedicated to ETHDs.

The main contributions presented in this chapter can be summarized as follows:

- A design space for interaction techniques dedicated to ETHDs for surface exploration.
- A set of 5 interaction techniques involving the exploration of a wide and flat surface.
- A use-case scenario to contextualize the application of the conceived techniques for haptic exploration in the task of shape coloring.
- A user study for assessing the performance of the proposed interaction techniques, both with quantitative and subjective measurements.

This chapter is structured as follows: The proposed techniques are introduced and explained in Section 3.1. The use-case scenario for contextualizing our approach is showcased

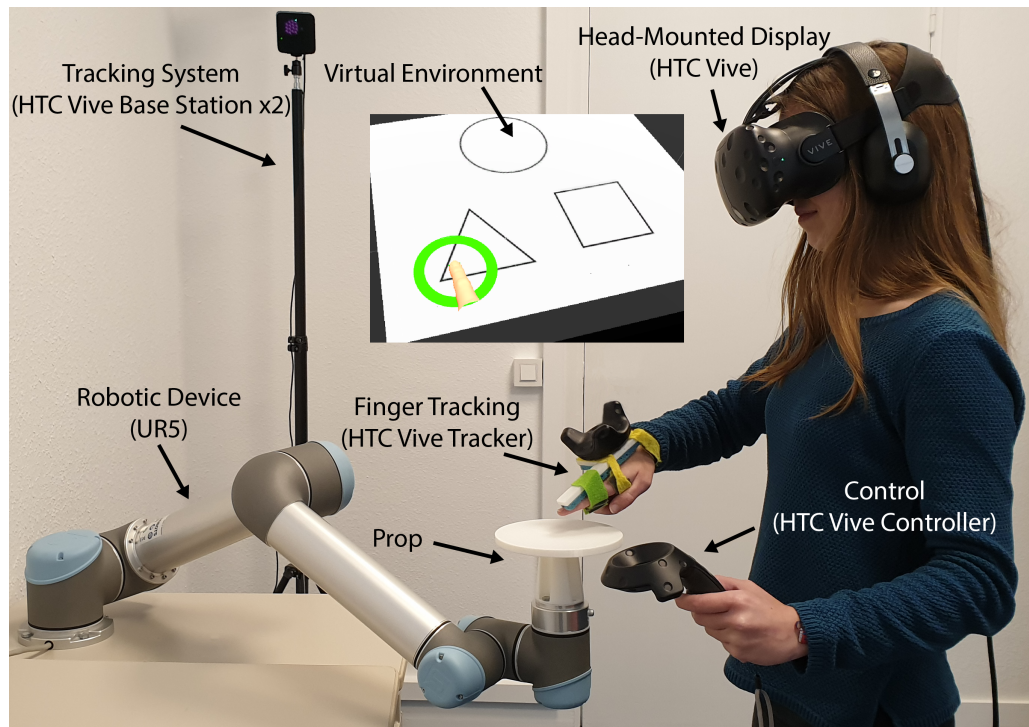


Figure 3.1 – Global setup of our system. The grounded ETHD system (bottom-left) renders a large flat surface by positioning a physical prop (bottom-center) under the user’s finger using different interaction techniques. The task proposed in our use-case scenario consists in shape coloring in a VE (top-center). The user tracking system comprises the HTC Vive Base Stations (top-left), the Vive tracker and controller (middle-center) and the Vive HMD (top-left).

in Section 3.2. Section 3.4 presents the user study carried out to evaluate the formerly introduced techniques. Results and insights from the user study are discussed in Section 3.5. Finally, general remarks and conclusions are commented in Section 3.6.

This chapter presents a contribution to ETHDs **usability** by addressing the research questions related to interaction technique design (RQ2) and large surface rendering (RQ3).

3.1 Interaction Technique Design

We proposed a design space for conceiving interaction techniques for surface exploration with ETHDs. These techniques intend to increase ETHDs usability when users explore large surfaces in a VE. This design space considered four levels that intend to describe the interaction process between the user and haptic display. Later, a set of five

interaction techniques were conceived by exploring the different combinations of the design space's features.

3.1.1 Design Space

The design space and its different levels were chosen according to the chronological order of each feature during the interaction process. This design space is divided first by the two input possibilities: motion or controller input. This design space level is justified under the reason that input represents the basic feature of the ETHD interaction process since it determines how the user is going to instruct the system to displace the surface display to a new position. Movement control is considered on the next level since it involves task execution. Then, displacement represents the latter part of the task planning since it relates to how the next system's position is going to be reached. On the last level, we considered the contact feature. Normally, ETHDs require to have intermittent contact with the surface to be touched [2]. In this work, we decided to explore the efficiency of this approach but also considered the alternative of being always in contact with the device's surface display.

The properties of the four different levels of the design space are described below.

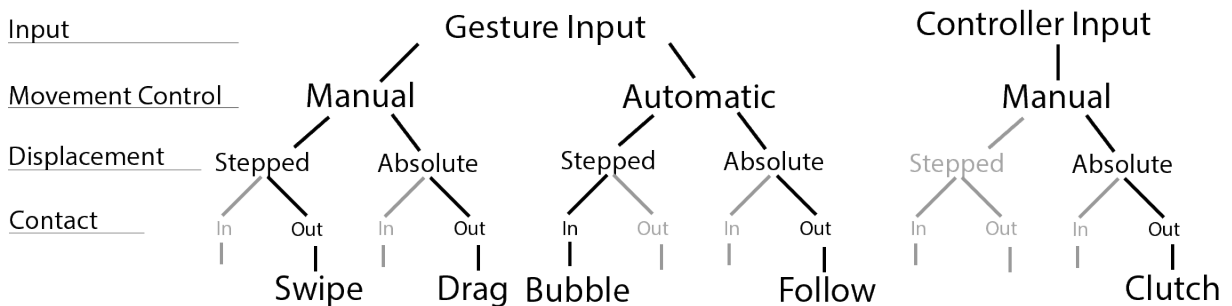


Figure 3.2 – The ETHD Interaction Technique Design Space.

3.1.1.1 Input

This level represents the input given to the system as a means to activate the interaction technique or any of its phases. This level was considered as part of the design space since it represents the first part of the process for "controlling" an ETHD. The two different branches of this level are:

- *Controller input.* The system is controlled with the help of an external device.

- *Gesture input.* The system is controlled by gestures performed by the users' hands.

3.1.1.2 Movement Control

This level represents whether the movement is automatic after the command or if it needs manual input to go to the next position for rendering the contact area. The two different branches of this level are:

- *Manual.* The user actively chooses the next position and gives the command for the system to move to a determined position.
- *Automatic.* The system is in charge of automatically displacing the contact area based on the given input.

3.1.1.3 Displacement

This level represents whether the surface display can directly be displaced to a selected position or if it can only reach the desired position through gradual movements. The two different branches of this level are:

- *Stepped.* The contact area is displaced over gradual steps towards a direction specified by the user.
- *Absolute.* The user chooses the next position of the contact area: Then, the system displaces physically the surface display to the previously specified location.

3.1.1.4 Contact

In this level, user contact is considered as a variable. It allows evaluating whether a continuous or intermittent contact could be beneficial for both directing the new area of an ETHD and large surface perception. The two different branches of this level are:

- *In-Contact.* The user is in constant contact with the surface while displacing the contact area.
- *Out-of-Contact.* The user is in intermittent contact with the surface while displacing the contact area.

The different branches of the presented levels can be combined to create interaction techniques for surface exploration with ETHDs. The branch of automatic action triggered by controller input is discarded since no user input can be used in this case. The design space portraying all the different level combinations is illustrated in Figure 3.2.

3.1.2 Interaction Techniques

A set of five techniques presented in this chapter was designed to illustrate different branches of the design space. The diagram presented in Figure 3.2 describes the design space organization and the positioning of each interaction technique. Figure 3.3 illustrates the behaviors of the different techniques.

Different branches of our proposed design space were explored through the creation of interaction techniques dedicated to addressing ETHDs' limitations in terms of surface exploration, lag, and unexpected collisions. The limited surface exploration issue was addressed by relying on the different iterations of our interaction technique design space as well as two types of surface contact: In-contact and out-of-contact. The in-contact branch feature was included to verify if constant contact with a moveable surface renders a sensation of touching a large surface. The out-of-contact feature considers the alternative to be in intermittent contact with the tangible surface as in common ETHDs. The lag issue was addressed by considering two different parameters on the displacement feature in the design space. The stepped displacement branch considers a fast, short movement that happens after the input is received from the user. The absolute displacement feature branch considers a large range movement which indicates the time taken by the robot to move from one position to another. Therefore, we intended to explore a fast and short movement versus a slower and larger one but with visual progress feedback. The issue of unexpected collisions with users was addressed by visually representing the contact area and adding a color code indicating when the robot was in movement (see Figure 3.3). Additionally, a visual cue was included in all the techniques implementations to indicate users when an area could not be reached by our system.

3.1.2.1 Swipe

The Swipe technique takes into account the gesture of swiping the contact area for displacing it. This technique was conceived for providing an interaction similar to the gesture used on touch screens for scrolling through a user interface bigger than the screen. The features of the swiping gesture such as out-of-contact control as well as a fixed and stepped displacement are considered as variables of the design space. The swipe direction is taken into account for displacing the contact area over a predefined distance of 15 cm in our system (1.5 times the diameter of the contact area). The users can reach the desired position through a series of swipe gestures. This technique was designed for bringing

up the familiarity of the gesture on ETHD’s surface displays with the gesture on touch screens. The technique profits also from the similar properties of intermittent contact when interacting with touch screens or with ETHD systems.

3.1.2.2 Clutch

The Clutch technique represents the possibility of using a controller as an input method for controlling the system actions. When users can control the ETHD’s surface display displacement, they can also acknowledge that the contact area rendering and robot displacement could be managed similarly to many other types of technological devices. The elapsed time and precision of the task fully rely on the user. This technique allows users to initiate the robot’s movement in the desired direction to continue their haptic exploration by pressing a controller’s trigger. While the trigger is pressed, the user can select the next position of the ETHD system with his hand interacting with the contact area. Releasing the trigger will select and fix the new position. This technique allows the user to know the position of the new contact area and also provides feedback on the elapsed time for the new surface to be loaded. The Clutch technique relies on having intermittent contact with the surface, thus only allowing contact when the surface is loaded. This technique was conceived considering the clutching procedure for 3D manipulation presented in the work by Bowman et. al [90] and translated to haptic devices in the work of Dominjon et. al. [91]. In our ETHD system, the procedure is mainly divided into pressing and releasing the trigger of the Vive controller. When pressing the controller, users need to raise their fingers up and outside the contact area. This gesture activates the projection of the auxiliary contact area, which indicates the next position of the system. Users move their fingers to displace this auxiliary area to the next position that they want to touch. Once they make their choice, users release the Vive controller trigger and wait for the area to be rendered. Visual feedback is displayed showing how the first area turns red and disappears while the selected area turns green and appears. After the animation, users can touch the contact area.

3.1.2.3 Drag

The Drag technique consists of displacing the contact area by following the user’s finger position. The user triggers the technique by elevating the finger over the surface and selects the desired position by lowering it down. This technique provides feedback on the time taken by the surface to be rendered (see the color modifications in Fig. 3.3) and

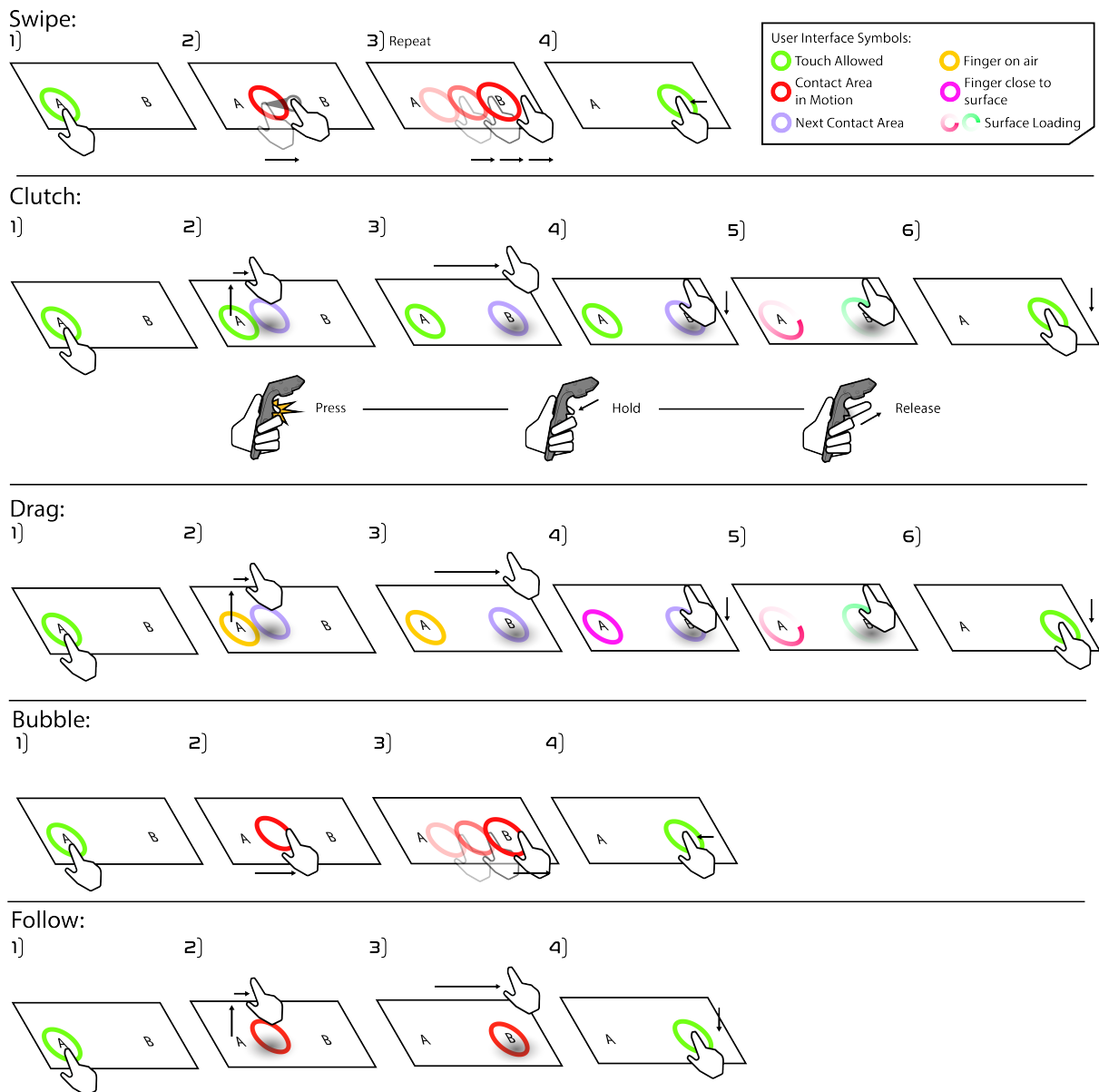


Figure 3.3 – Interaction Techniques. This figure illustrates the different interaction techniques designed by following different branches of our design space. The Swipe technique consists in performing a swipe gesture for displacing the contact area. The Clutch technique uses the Vive controller to trigger the contact area selection and displacement. The Drag technique permits the user to select and displace the area to be touched. The Bubble technique relies on touching the border of the contact area to displace it over a fixed distance. The Follow technique automatically follows the user’s finger while the latter is hovering on air.

also permits the user to know the location where the contact area will be located next. This technique was inspired from the HCI domain with the drag metaphor that is used for selecting an object and then dragging it into another position [90]. The procedure consists of a series of steps: first, users need to raise their fingers up and outside the contact area. Then, the performed gesture activates the projection of the auxiliary contact area, which indicates the next position of the system. Users then move their fingers to displace this auxiliary area to the next position that they want to touch. Once they make their choice, users lower down their fingers to activate the area selection. A visual feedback is displayed showing how the first area turns red and disappears while the selected area turns green and appears. After the animation, users can finally touch the contact area. This technique is similar to the Clutch but it differs on the input method. For selecting the next contact area, users have to lower their fingers enough to trigger the command of the robot. Then, the robot moves the surface display below the finger yet high enough for not touching the physical system while this one is moving. Both Drag and Clutch techniques provide visual feedback corresponding to the time taken for the robot to go from one position to another. This feedback helps users to understand the time needed to go all over a long distance between two positions. This feedback is inspired by the Timer technique presented in Chapter 2.

3.1.2.4 Bubble

The Bubble technique was inspired by the work of Dominjon et. al. [17]. It consists in displacing a "bubble" around the contact area. The contact area is constantly displaced below the user's finger. This technique was designed to take into consideration a constant contact with the surface display through the surface haptic exploration.

To control the motion of the contact area, users need to displace their fingers to touch the border of the contact area (or bubble) to trigger the movement. The movement is executed in the direction established by the vector starting from the contact area center to the contact point. For deactivating the movement, users need to release their fingers and not touch the border zone. When the users are inside the bubble, they can freely move their fingers without modifying the position of the contact area.

3.1.2.5 Follow

The Follow technique provides constant feedback about the contact area position while it is displacing underneath the user. This technique is close to state-of-the-art methods

since the robot tries to reach the user’s finger position in real-time. The main difference between this technique and state-of-the-art ones is that there is visual feedback indicating a displacement of the contact area towards the target position. To control the motion of the contact area, users first need to raise their fingers up and outside the contact area to activate the technique. While the users’ finger is in mid-air, the contact area follows the finger’s position concerning the coloring area. The robotic system follows the user through a stepped movement series. The technique is deactivated when the user decides to touch again the virtual contact area.

3.2 Use Case

A use case was designed for testing the different interaction techniques on a scenario involving the exploration of a wide and flat surface. The considered scenario depicts a desktop surface located in a virtual room (see Figure 3.4). The task consists in coloring figures over a canvas. The coloring task involves the exploratory procedures proposed by Lederman & Klatzky [71] of lateral motion (coloring and being in constant contact with the surface) and pressure (triggering interaction techniques such as Bubble and Swipe). Users can explore the surface with each of the interaction techniques. The surface to be colored displayed three shapes: a circle, a triangle, and a square arranged on a canvas. The shape properties, size, and their location in the canvas represented different levels of difficulty to carry out the task.



Figure 3.4 – The VE depicting the use-case scenario. The environment was designed to give context to the task of coloring/painting.

Our proposed ETHD is based on a Universal Robots UR5 robotic arm. This robot received constantly trajectory-based linear movement instructions using as parameters

the users' fingers position in the VE and the robot's current position. Participants can touch the prop with the tip of their dominant hand's index finger. Participants can use their non-dominant hand for holding the Vive controller required for some interaction techniques.

The system uses an HTC Vive HMD tracker and controller for controlling the 3D interaction. The Vive tracker was attached to a hand strap with an integrated support used to constrain the index finger movement to favor the virtual representation of the finger and its positioning in the VE. The environment was created using Unity. Robot's communication with Unity is achieved through TCP port communication and parsing commands to the UR5 programming language and interface. The virtual simulation was run on a computer with an Intel Core i7-7820HQ processor with an NVIDIA Quadro P3000 graphics processor.

3.3 User Study

A user study was conducted to assess the performance and user experience for each interaction technique in the task of shape coloring on a virtual surface. Participants' responses were used to have a deeper insight of users perception for each technique in terms of precision, usability and efficiency.

3.3.1 Experimental Setup

We designed an experimental prop (surface display) which consists of a round flat surface attached to the UR5 end-effector (see Figure 3.1). The 3D printed surface has a radius of 8.25 cm. This radius size was motivated by adding space to be touched outside the virtual contact area which radius was 5 cm. This extra space was also considered for not disclosing the limited size of the prop's surface while performing the gestures for each interaction technique. The experimental setup is shown in Figure 3.1. Both prop and experimental setup were used for the use-case scenario previously described in Section 4.

3.3.2 Procedure

Participants were instructed about how to use each interaction technique without disclosing its concept name. Once participants confirmed that they understood each technique, they proceeded to begin the experiment. For each condition, participants were

required to complete a training task to get familiarized with each technique. Participants were asked to wear an isolating headphone set displaying white noise when participating in the experiment as a means to not perceive sounds produced by the robot while displacing the surface display. They could also control the volume in a range where they could not hear the robot noise without being annoyed nor distracted by the white noise. The participants were asked to paint the three shapes using their index fingers. They were allowed to displace the contact surface by using the tested interaction technique. Their objective was to be as accurate as possible during their painting task.

3.3.3 Experimental Design

We considered the five interaction techniques presented in Section 3.1. Each of these techniques was used as a condition for the virtual painting task. The order of these conditions was sorted using the Latin Squares method.

The experiment consisted of 5 blocks with 1 training trial and 3 experimental trials. Giving a total of 20 trials. Each trial had a maximum duration of 4 minutes. Participants were aware of the elapsed time during each trial by watching an integrated chronometer in the main UI. The 5 blocks were presented using the Latin Squares method.

3.3.4 Collected Data and Population

The collected data for this study concerned both results of the painting task performance and user experience (UX). The elapsed time for each trial was registered along with the paintings generated for each trial. The paintings were analyzed to count the quantity of painting inside (S_i) for every shape (j) (See Equation 1). Additionally, the overall quantity of spilled painting outside the shapes' borders (S_e). These factors were considered to calculate an error ratio (See Equation 2).

$$S_i = \sum_j^1 S_{ij} \quad (1) \quad \text{and} \quad \frac{S_e}{S_i + S_e} \quad (2)$$

Thereafter, we will use this ratio and express it as a percentage (named Painting Error Percentage). After the experiment, participants were asked to fill a user experience questionnaire (UEQ). This questionnaire integrated questions from [92] and [93], focusing on usability factors by asking the participants whether they considered the interaction techniques as controllable, captivating, innovative, pleasant, motivating, easy to learn, and

fast. The answer format for these questions was presented on a Likert scale. We gathered a total of 20 participants (6 female, 14 male), ages 22 to 33 ($M = 26.45$, $SD = 3.236$).

3.4 Results

The paintings produced by each participant were analyzed to assess the total amount of surface covered for all the shapes and the total amount of spilled paint outside the borders (See Fig. 3.5 for an illustration of three paintings with different levels of performance). The performance is summarized in Table 3.1.

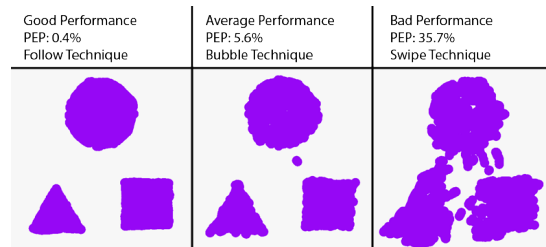


Figure 3.5 – The resulting participants’ paintings. The paintings were analyzed to count the number of pixels colored inside the shapes as well the outside ones to determine the performance for each technique. A good performance painting is shown on the left. Average performance is shown in the middle while a bad performance is shown on the right.

Technique	Time	PEP	ESCP	ISCP
Swipe	126 (38.4)	7.4% (4.8%)	2.1% (1.6%)	99.1% (1.1%)
Clutch	102 (30.4)	4.5% (4%)	1.2% (1.2%)	99.4% (0.7%)
Drag	118 (39.1)	4.7% (3.7%)	1.3% (1%)	99% (1.2%)
Bubble	103 (33.2)	6.8% (4.2%)	1.9% (1.3%)	99.3 (0.8%)
Follow	113 (39.5)	4.9% (3.6%)	1.3% (1.1%)	99.4 (0.7%)

Table 3.1 – Performance results for elapsed time and painting quality. The results (mean and standard deviation) are: average time (in seconds), painting error percentage (PEP), exterior shape coloring percentage (ESCP) and interior shape coloring percentage (ISCP). The PEP refers to a ratio considering both ESCP and ISCP defined previously in Equation 2.

To study the time needed by the participants to perform the task, we used a linear mixed model on the collected data for the interaction techniques. The participants were considered as a random effect in the model. Our analysis of variance showed a significant

effect on the techniques ($F(4, 262) = 6.37, p < 0.001$). We performed a post-hoc analysis using Tukey tests. Bonferroni correction was used for all post-hoc analyses. The post-hoc analysis revealed significant differences between the Swipe technique and: the Bubble technique ($p < 0.001$), the Clutch technique ($p < 0.001$) and the Follow technique ($p = 0.02$). We found also significant differences between the Drag technique and both Clutch ($p = 0.005$) and Bubble techniques ($p = 0.009$).

Concerning the analysis of the PEP, we used a linear mixed model on the collected data for the techniques. The participants were considered as a random effect in the model. Our analysis of variance showed a significant effect on the interaction techniques ($F(4, 262) = 16.51, p < 0.001$). The post-hoc analysis using Tukey tests revealed significant differences between the Swipe technique and: the Drag technique ($p < 0.001$), the Clutch technique ($p < 0.001$) and the Follow technique ($p < 0.001$). We also found significant differences between the Bubble technique and: the Swipe technique, the Drag technique ($p < 0.001$), the Clutch technique ($p < 0.001$), and the Follow technique ($p < 0.001$). Results on the subjective questionnaire are summarized in Figure 3.6.

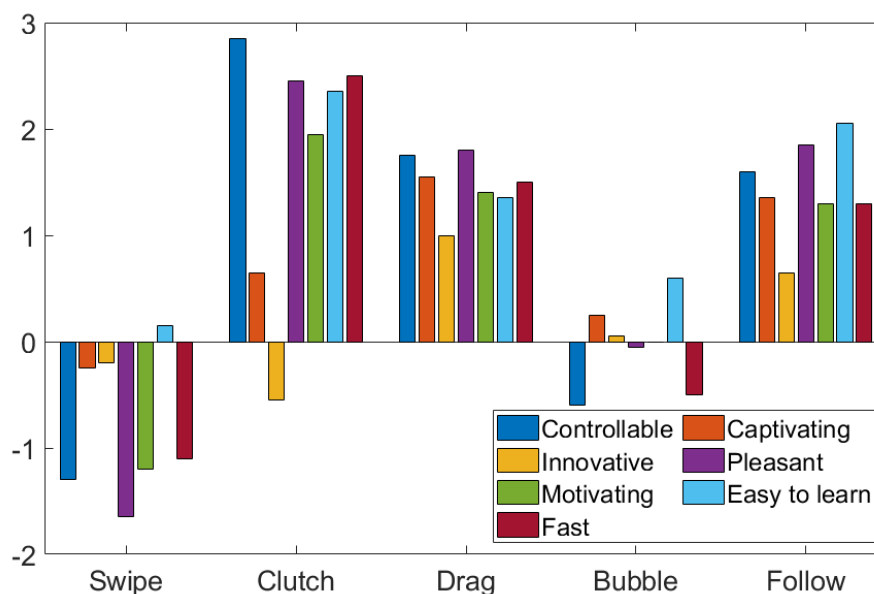


Figure 3.6 – User Experience Questionnaire Results. The average scores for several features evaluated in the subjective questionnaire. The results are depicted on a scale ranging from -3 to 3.

To study the answers of the subjective questionnaire, we used linear mixed models on the collected data for each of the 7 criteria with respect to the interaction techniques,

namely: controllable, captivating, innovative, pleasant, motivating, easy to learn, and fast. The participants were considered as a random effect in the model. Our analysis of variance showed a significant effect on the interaction techniques for 5 criteria: *Controllable* ($F(4, 76) = 7.62, p < 0.001$), *Captivating* ($F(4, 95) = 15.28, p < 0.001$), *Motivating* ($F(4, 76) = 5.96, p < 0.001$), *Easy to learn* ($F(4, 76) = 6.043, p < 0.001$), and *Fast* ($F(4, 76) = 5.96, p < 0.001$). No significant effect was found for the *Innovative* criterion ($p = 0.17$) and the *Pleasant* one ($p = 0.32$). However, several participants qualified the Drag as an innovative technique. In their own words: "Favorite technique due to the time guidance for the activation of the zone", "The one I loved the most! Most innovative one and very quick with good control", "Great one, pretty convenient and one-handed".

Concerning the *Controllable* criterion, post-hoc analysis revealed a significant difference between the Clutch technique and: the Bubble technique ($p < 0.001$), the Follow technique ($p = 0.006$) and the Swipe technique ($p = 0.003$). There was also a significant effect between the Drag technique and: the Bubble technique (< 0.001), the Follow technique ($p = 0.004$) and the Swipe technique ($p = 0.002$). Participants qualified the Clutch technique as the most controllable, yet the most conventional. In their own words: "Easy to control, but need an extra hand", "Nice, simple, the trigger gives you control, you decide WHEN you want to move the circle", "Intuitive but perhaps "old-fashioned" in this type of VR environment".

Concerning the *Captivating* criterion, post-hoc analysis revealed a significant difference between the Bubble technique and: the Drag technique ($p < 0.001$), the Clutch technique ($p = 0.002$) and the Follow technique ($p = 0.03$). A significant effect was also found between the Swipe technique and: the Drag technique ($p < 0.001$) and the Clutch technique ($p = 0.03$). Finally, a significant effect was found between the Drag technique and: the Follow technique ($p < 0.001$) and the Clutch technique ($p < 0.001$). Participants rated both Drag and Follow as the most captivating techniques.

Concerning the *Motivating* criterion, post-hoc analysis revealed a significant difference between the Swipe technique and all other interaction techniques: Bubble ($p < 0.002$), Clutch ($p < 0.001$), Drag ($p = 0.007$) and Follow ($p < 0.001$). The Swipe technique received comments from the users concerning their frustration of not being able to control or to extend the distance with a stronger gesture. In their own words "I really don't like it. It was frustrating not being able to control how large is the swipe movement".

Concerning the *Easy to learn* criterion, post-hoc analysis revealed a significant difference between the Drag Technique and: the Bubble technique ($p < 0.001$), the Clutch

technique ($p = 0.03$) and the Follow technique ($p < 0.001$). There was also a significant difference between the Swipe technique and: the Bubble technique ($p = 0.002$) and the Follow technique ($p = 0.01$). According to participants' comments, the Clutch technique was noted as the easiest technique to learn. In their own words: "Fast progression with this one, perhaps for people with VR experience", "Using a controller for changing painting mode to moving mode was as easy as the method C (Drag)". Concerning the Swipe technique, participants commented that its concept was easy to understand but that it took them some time to master it.

Concerning the *Fast* criterion, post-hoc analysis revealed a significant difference between the Bubble technique and: the Drag technique ($p = 0.01$), the Follow technique ($p = 0.01$), and the Swipe technique ($p < 0.001$). There was also a significant difference between the Swipe technique and the other techniques: Clutch ($p < 0.001$), Drag ($p = 0.03$) and Follow ($p = 0.03$). Both Bubble and Swipe techniques implemented the stepped displacement. Participants commented that they appreciated the techniques format, but they made emphasis on the time that it took them to reach the desired position. In their own words: "(Bubble) Good control, but a little bit slow". In the case of the Bubble technique, these comments contrast with the fact that this technique achieved the second shortest average trial time.

Concerning other factors such as presence in the VE, we informally received feedback from the users arguing that the Clutch and Drag techniques were the ones providing a more realistic experience to touching a flat, wide surface. In their own words: "I think it (Drag) offers the best compromise in terms of immersion and performance since it feels very precise". And "(Clutch) Using the controller blocks one hand and kind of breaks immersion".

3.5 Discussion

This chapter studies a design space where several interaction techniques can be conceived by combining diverse parameters aiming to address the common issues that ETHDs present, namely, lag, limited, contact area, and unexpected collisions. For instance, the displacement feature in the design space addresses lag and contact area limited size by considering providing a stepped but immediate surface display displacement and thus rendering in a fast manner a new area to touch. The integrated visual feedback indicates the system's current position to avoid unexpected collisions and to inform users about

the size and location of the contact area.

The techniques studied in this chapter are an exploration of several branches of the design space. The possible combinations provided by the design space are too many to be properly evaluated in one study. Thus, we decided to implement techniques that could represent at least one of the features proposed in the design space. Future work could explore new techniques conceived under our design space to study their performance in different scenarios and tasks. Under this framework, we already designed a set of 5 techniques: Swipe, Clutch, Drag, Bubble, Follow. To further study the performance of these techniques, a use-case scenario was designed to contextualize a task that required rendering a large contact area and a constant interaction between user and surface. The chosen task was to color shapes with the index finger since it is adapted to the system's configuration and to an interaction that requires large surface exploration and constant contact with the surface. A user study was conducted to assess the coloring task performance and user experience. This was done as means to understand the efficiency and usability of our techniques in a context adapted to ETHDs as well as a means to test different possibilities of our design space.

Primarily due to safety reasons, users need to be aware that they are interacting with a grounded robotic system. Therefore, we proposed interaction techniques with dedicated visual feedback. Providing feedback that indicates when to touch the surface and the process of translating the surface display to another location is useful for users to cope with the system limitations. Thus, comments from users pointed out that visual feedback was appreciated as it helped them to understand when they could be able to touch the contact area. The feedback corresponding to *contact area loading* has already been considered in the work of Abtahi et al. [15] and Posselt et al [2]. The feedback corresponding to *location selection* that involves absolute surface display displacement such as in Clutch, Drag and Follow techniques has also been considered in the work of [2] where users were able to select the texture to be touched so the robot could afterward move to a position where the texture could be located. Results from the user study suggest that absolute surface display displacement performs better than an immediate short stepped displacement. These techniques additionally had the lowest scores concerning painting error.

The integration of gesture commands to displace the contact area of an ETHD has been considered in previous work [30], [53]. Incorporating gesture-based interaction techniques requires considering the differences between the gestures and the hand movements that will occur during the interaction. Results from this study suggest higher performance

when gestures are mostly different from coloring the task such as the ones used on Drag or Clutch techniques. On the opposite side, the similarity between the swipe and coloring gestures confused users at the moment of learning how to control the interaction technique on the experimental task. The integration of a controlling device for ETHD interaction could be taken into account when training the user to learn to control the system. The inclusion of the controller does not have to interfere with the haptic perception but only to work as a tool for selection. Comments from users suggested that the controller helped them to separate the task of selecting the contact area and touching the surface. Users qualified Drag as the most innovative technique since it does not involve a controller and overall it was the second-best rated technique. Remarks from participants over Drag suggested the opportunity of changing the gesture of lowering down the finger for selecting the contact area to a more precise gesture. Results from this study suggest that the Drag technique (which shares almost every feature with Clutch except the usage of a controller) can be considered as a technique to be integrated in the future. The arguments in favor of this technique mostly rely on the usage of natural gestures to point and select the contact area. Results in time performance indicate the Drag and Follow techniques had the greater amount of time elapsed by the users. This might be due that these techniques required pointing towards the desired contact area [94], [95] and Fitts' Law [90], [96]–[98] as shown in the research of Bruder et al. [99] and Chun et al [100]. In addition, the presented shapes had also different levels of complexity in the coloring task. For instance, the triangle had narrow angles that complicated the task but the initial position was always close to this shape. The circle on the other hand was the easiest to color since there were no corners and it coincided with the brush shape yet it was the furthest shape from the starting point. The square provided a balance between difficulty, size, and distance to the user. The work of Arora et al. [101] suggests taking into consideration the complexity of the shape to be colored in the task. Efforts focused on 2D interaction for ETHDs also looked for increasing the contact area through active surface rendering such as physical surface display rotation [102] and pin-array-based surface rendering [30]. Other methods have been considered such as using virtual redirection [47]. While the Drag and Clutch techniques had a good performance in the user study, we recognize that their features can be challenged in other scenarios. The proposed set of techniques could be further studied concerning their performance in conditions where the geometry to be explored possess more complex properties. For instance, the Bubble technique could not be suited for curved surface exploration. Through the use of our design space, future

work could consist in designing new interaction techniques and testing them in other scenarios. Combining ETHDs and VEs can lead to optimizing the amount of tangible surface needed to provide a convincing sensation of touch in a virtual simulation. Results from this study suggest that an adequate interaction technique that profits from the ETHD features can not only provide the sensation of touching a large object but also optimize task performance and UX. Besides task performance and UX, others factors are worth to be explored in future work. Namely, overall ETHD efficiency in providing haptic feedback in VR, ETHDs performance against other types of haptic displays such as wearable ones, and user presence in a system combining both ETHDs and VEs.

3.6 Conclusion

This chapter presented a study of interaction techniques for ETHDs for surface exploration. These techniques were conceived within a design space comprised of four features: input, movement control, displacement, and contact. Using this design space, several feature combinations were explored for conceiving 5 techniques: Swipe, Clutch, Drag, Bubble, and Follow.

A use-case scenario was created to contextualize the application of these techniques. The task of surface coloring over a digital canvas was chosen as it involves a large and constant surface exploration. A user study was conducted to evaluate the techniques' performance in matters of accuracy and elapsed time taken for a shape coloring task. In addition, we qualified the UX perceived by users as a means to identify the features that were better evaluated by users.

Results pointed out that the Clutch and Drag techniques had a good performance in matters of low PEP and UX. The features shared by these techniques are absolute displacement, out-of-contact triggering, and user-controlled motion. Participants commented that the visual feedback displayed with these techniques helped them to better understand the surface rendering process.

Taken together, the contributions presented in this chapter could help to the design of novel interaction techniques adapted to a wider range of tasks, actuators, and surface displays.

ALLOWING LARGE, MULTI-TEXTURED SURFACE RENDERING FOR ETHDs

The state-of-the-art in ETHDs shows that the size of the haptic feedback is primarily limited to the size of the surface display being held by the device. This issue reduces the exploration area at the moment of interacting in a VE where an ETHD is integrated. Additionally, the necessity of having multiple textures to be provided as a part of haptic feedback is gaining importance for increasing the diversity of rendered surfaces [2], [3], [20].

In this chapter, we propose a novel ENcountered-Type ROTating Prop Approach (ENTROPiA) for displaying haptic virtual surfaces based on ETHD without the constraint of a limited surface area to be in contact with. Our approach relies on a rotating surface as a means to display a large surface (see Figure 4.1). This approach relies on having the users in contact with a spinning round surface that a robotic system can position and rotate according to the users' hand location. The sensation of touching a flat surface is given by the sliding movement of the prop under the users' finger and the integration of an interaction technique that guides users in the surface exploration. The interaction takes place in a VE using an HMD and a tracking system. Users can touch different textured surfaces in a VE by following a trajectory that allows them to explore a large surface with their sense of touch.

The main contributions presented in this chapter can be summarized as follows:

- A novel approach for unconstrained large surface haptic rendering leveraging ETHDs and introducing a rotating prop.
- A proof of concept illustrating our proposed approach.
- A user study assessing haptic perception provided by our approach and comparing it to the state-of-the-art on large shape rendering techniques for ETHDs.

This chapter presents a contribution to ETHDs **haptic feedback** by addressing the

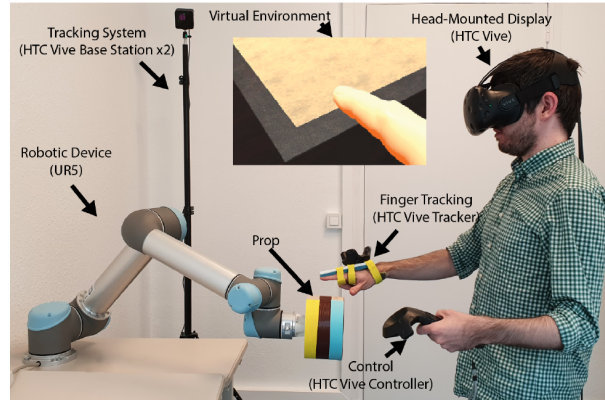


Figure 4.1 – Global setup of our system. Our proposed rotating prop (bottom-center) can provide a large haptic surface display together with different textures represented in a VE (top-center).

research questions related to large surface rendering (RQ3) and multiple texture rendering (RQ4).

The remaining of this chapter is organized as follows: Our approach is introduced in Section 4.1 along with its main components. Section 4.2 presents the design of a proof of concept that contextualizes the contributions of this chapter. Later, Section 4.3 describes a user study conducted for evaluating the rendering perception for our approach. Results of our approach performance in the user study are presented in Section 4.4. These results are discussed in Section 4.5. The chapter ends with a general conclusion.

4.1 The ENTROPiA Approach

Our objective is to provide a large haptic surface rendering that could benefit from the ETHD property of having an unconstrained, free-hand interaction. However, current limitations on the ETHD field are mainly based on not having a large surface that could be touched in a continuous, natural manner. To do so, we leverage a grounded ETHD by providing a larger contact area rendered by the integration of a rotating prop and an interaction technique that allows touching a defined, virtual surface.

The principle (see Figure 4.2) relies on having users' in contact with a spinning round surface which a robotic system can position and rotate according to the users' hand location. The sensation of touching a flat surface is given by the sliding movement of the prop under the finger and the usage of an interaction technique that exploits this approach.

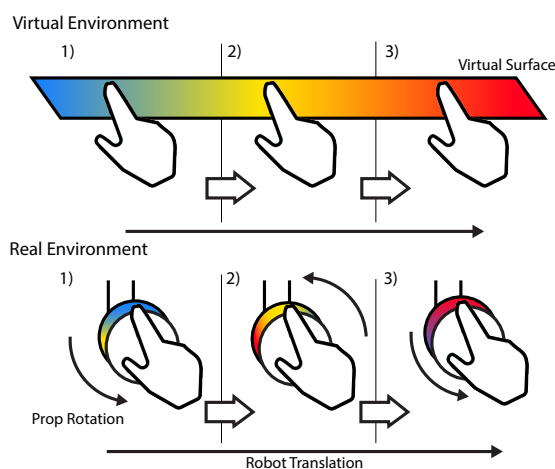


Figure 4.2 – The ENTROPiA principle. The sensation of touching a flat surface in a VE is given by touching the rotating prop and simultaneously displacing it through the same trajectory and speed of the users' fingers. Considering the prop size and shape as well as both translation and angular speed, users are always in contact with a "flat face" that continuously renders itself at the same time when they displace their fingers.

As the finger displaces while touching the surface, the round prop rotates and displaces in the same trajectory to always provide an area to be in contact with. Profiting from its curvature, the round prop rotates in the opposite direction of its displacement thus creating the sensation of continuously touching a large flat surface without the necessity of physically having a surface of the same shape and dimensions as currently done in state of-the-art approaches. Additionally, this principle permits to increase the contact area of traditional ETHDs by compensating their actual mobility range and their surface display size and volume as a means to render any required surface.

The prop can be either integrated directly onto the ETHD end-effector (see Figure 4.3) or can be integrated with the aid of a spinning motor.

The key components of our approach are:

1. An encountered-type haptic display composed of a grounded Universal Robots UR5 robotic arm, a Vive HMD for displaying the virtual environment, a Vive tracker and base stations for tracking users' hand position and a Vive controller for controlling the simulation (See Figure 4.1).
2. A cylindrical prop containing textures all over its circumference, giving the sensation of touching an infinite surface while rotating below users' fingers (See Figure 4.3).
3. An interaction technique for guiding users when performing the exploratory haptic

procedure.

The integration of these components enables large, multi-textured surface rendering. The presented prop integrates several textured stripes that surround its curved side. By covering the entire circumference of the curved part of the prop, our approach can render an infinite textured surface as long as the system can place the prop and spin it under the user's finger.

4.1.1 Rotating Props

Our prop permits to have contact over its curved side. By spinning the cylindrical prop, the robot keeps the user in contact with the face of the prop. As long as the user follows the contact area, the surfaces to be touched are only limited by the range of mobility of the robotic device rather than the overall volume and area of the prop itself.

The prop's height permits to include several textures over its surface which can cover the whole circumference or just a part of it for having a shorter contact area but for increasing the texture range. The influence of the prop's radius permits to render the sensation of touching a flat surface while spinning since touching with one finger a part of its circumference does not disclose the prop's cylindrical shape. Therefore, it is possible to obtain a contact area greater than the prop's diameter by rotating and displacing it under the users' fingers.

4.1.2 Interaction Technique

Our exploratory interaction technique relies primarily on having a contact area that moves on a predefined trajectory. The contact area is conceived for a one-finger interaction to couple with the geometrical properties of our prop for rendering the sensation of touching a flat surface. Our interaction technique is inspired by the work presented by Posselt et al. [2] in which the authors propose a technique for profiting from the workspace given by a polyhedral ETHD prop. This technique consists in displaying the possible areas that users could touch in a multi-textured VE simulating a car cockpit for automobile design. Once the user chooses an area the grounded ETHD system placed a face of the prop to that area that corresponded with the texture of the virtual object. Users were always informed of the available touch workspace with the aid of a visual cue that signaled the borders and shape of the polyhedral prop's face. Currently, state-of-the-art in ETHDs proposes interaction techniques that limit the contact to the area of their device's surface



Figure 4.3 – The designed cylindrical prop for representing our approach. This prop can hold different textures which are used to render flat surfaces in a VE. Textures such as cork, foam, felt, leather, cardboard and wood are displayed on this figure. In this case, the leather texture covers the prop’s whole circumference, this permits to render this texture in an infinite way as long as the prop spins below users’ fingers.

display. In our interaction technique, a colored surface is displayed on a VE where the user can touch the contact area represented by a square. The squared contact area was designed to guide the users and to prevent them from sliding to an undesired part of the prop and thus mismatching what they see in the VE and what they feel with their sense of touch. Users are asked to touch the squared area with their index finger as a means to optimize hand and finger tracking and to have a contact area proportional to the size of the prop (see Figure 4.4).

Our exploratory interaction technique has three phases:

1. *Ready Phase.* The contact area is colored orange and users are prompted to move their fingers from the resting location to touch the contact area.
2. *Touch Phase.* The contact area is colored blue and participants are asked to touch and follow this surface. The contact area is displaced over a virtual surface matching the trajectory of the passive prop surface.
3. *Release Phase.* The contact area turns red and users are prompted to release the finger from the surface and maintain it around the waist level for avoiding unexpected contact with the prop if re-positioning the robot’s surface display.

Thanks to our interaction technique, the user is permitted to perform a haptic ex-

Figure 4.4 – ENTROPiA Interaction Technique. This technique enables the user to explore a surface and its texture in a VE. The phases of the technique are represented both in the VE and in real life with the prop. The contact area is represented by a colored square that displaces over a surface in our VE. On the ready phase, the contact area becomes orange telling the user to be ready for movement and to touch the square. On the touch phase, the colored square becomes blue and displaces over the surface. The user is in constant contact with the surface in this phase as a means to haptically explore the surface. The release phase prompts users to lift their fingers to stop contact with the device.

ploratory procedure in a defined area of a VE. This technique integrates with our proposed prop for increasing the contact area of a haptic area and thus moving towards the ETHD.

4.2 Proof of Concept

We designed a proof of concept to showcase the possibilities of ENTROPiA. This section comprises the description of the hardware we used to implement this proof concept as well as the scenario that contextualizes our approach and the virtual environment that integrates both the system implementation and the scenario metaphor.

4.2.1 Setup

The system was implemented with a Universal Robots UR5 robotic arm. This robot was programmed with several movement routines for displacing and/or rotating the surface display for recreating a flat surface. Users have contact with the surface with the tip of their right index finger. Participants used their left hand for using the Vive controller for navigating through the experiment user interface. The system uses an HTC Vive HMD tracker and controller for displaying and controlling the virtual simulation. The Vive tracker was attached to a support that constrained finger movement on the right hand for only letting the user touch the prop with the index finger (see Figure 4.8).

Robot's communication with Unity was achieved through TCP port communication and parsing commands to the UR5 programming language and interface. The VE was implemented on a computer with an Intel Core i7-7820HQ processor with an NVIDIA Quadro P3000 graphics processor. The designed prop consists of a cylindrical shape with a radius of 8.4 cm and 10 cm in height. The prop was displaced 17 cm to the right at a



Figure 4.5 – The scenario setup for the studio. Our approach is integrated in this virtual scenario to render the sensation of the textures located on the desktop.

speed of 0.05 m.s. When rotating, the prop had an angular velocity of 0.2 rad.s

4.2.2 Scenario

The VE displays a studio where different flat textures can be explored (see Figure 4.5). A classic covered desktop was chosen as the main feature to be touched in this scenario since portrays different textures that are frequently found in that context. In this environment, the user can touch four different materials: the desktop wood, a leather cover for the desktop, a sheet of paper for representing documents and planes and the glass of a photo frame. The materials were assigned to the different elements present in the environment. The wood was assigned to the desktop while leather, paper and tempered glass were assigned to a desktop cover, a print and a photo frame respectively.

4.3 User Study

We conducted a user study to assess haptic perception of virtual surfaces simulated by our approach and to compare it with state-of-the-art surface rendering techniques as well as the ground truth perception.

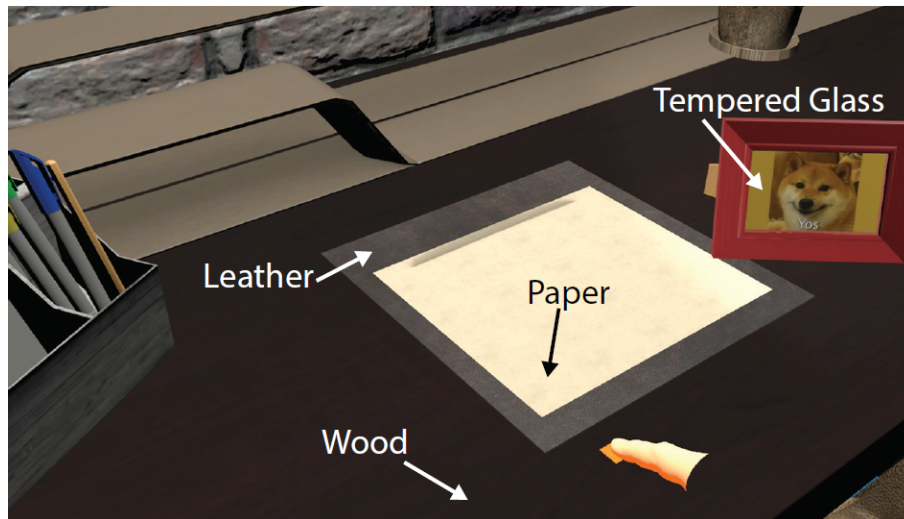


Figure 4.6 – Details of the virtual scenario. The VE was designed to mimic a desktop in a studio where different textures could be touched in different objects such as a wooden desktop, a leather cover, and a sheet paper. The photo frame could also be touched by using the state-of-the-art approach.

4.3.1 Experimental Design

Four surface haptic display methods were considered in our experimental design. These display methods consider both our and state-of-the-art approaches to be compared against the ground truth as a way to determine which approach renders haptic feedback that could be perceived as touching a flat surface. The four haptic display methods were the following:

- Ground truth (GT): A large flat surface is touched and used as a reference for comparing to the other type of surfaces rendered. The GT is represented as the largest part of the experimental prop.
- Translating Flat Surface (TFS): The smallest rectangular side of the experimental prop was used as the contact area. The surface was displaced but not rotated. This haptic display represents the current state-of-the-art approach since it primarily considers the flat surface display’s commonly used in ETHD reported literature.
- Translating and Rotating Round Surface (TRRS): This condition represents ENTROPiA. One side of the cylindrical part of the prop was used as the contact area. The surface was displaced and rotated. This haptic display represents our approach of increasing a haptic device contact area without the necessity of having a large physical surface.

- Translating Round Surface (TRS): One side of the cylindrical part of the prop was used as the contact area. The surface was displaced but not rotated. This haptic display represents an intermediate phase between the state-of-the-art and our proposed approach. The user touched one part of the experimental prop’s circumference while the latter was displaced by the robotic system. This haptic display was considered to evaluate if users could perceive a flat surface by touching a curved non-rotating surface.

The hypothesis of our experiment was the following: the sensation of touching a flat surface can be obtained if users displace their fingers over the round part of a cylindrical shape while the latter is spinning and moving.

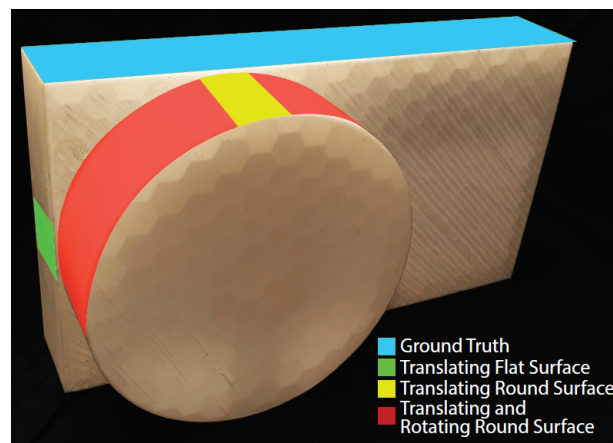


Figure 4.7 – The experimental prop. A rectangular prism was attached to the back of our proposed prop as a means to have different alternatives to be compared against the GT which is depicted on the longest side of the prop. For the TFS users touched the shortest flat surface of the prop. The TRS is represented by one small part of the prop’s circumference. The TRRS represents our novel approach and comprises the whole cylindrical surface that users touched while the prop translated and rotated at the same time. This shape recreates the same approach used in our proof-of-concept.

4.3.2 Experimental Setup

A multi-sided prop was designed to comprise on different conditions, compared against the sensation of touching a flat surface representing the ground truth. The experimental prop possesses a cylindrical shape that measures 8.4 cm in radius and 10 cm in height attached to a rectangular measuring 30 * 15.5 * 5 cm. The longest face (see Figure 4.8 bottom-right) is used to represent the ground truth. The shorter face of the prism was

used to depict the ETHD’s state-of-the-art static surface approach. The cylindrical part of the prop is also attached to represent the ENTROPiA approach.

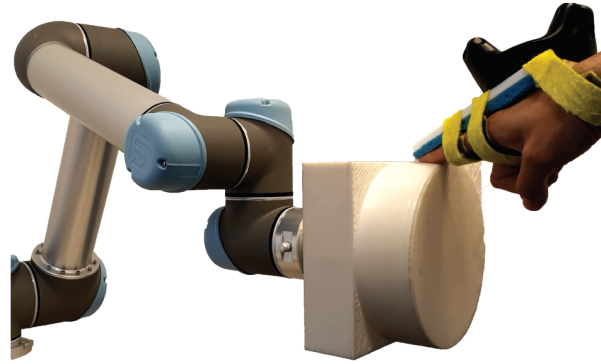


Figure 4.8 – Experimental setup. The hand support used for fixing the users’ hand position and for sustaining the Vive tracker (upper right) and the multi-sided experimental prop with a flat surface integrated (center) this experimental prop was displaced and rotated by a robot unit (left) for having an ETHD-based approach.

4.3.3 Procedure

Before getting involved in the experiments, participants were asked to fill a consent form and were informed that they were going to interact with a robotic device. Participants were equipped with a headset for listening to white noise while participating on the experiment so as to not perceive sounds produced by the robot while displacing the surface display. Each trial of the experiment comprised two stimuli. The first stimulus or the ground truth consisted on touching the longest flat side of the experimental prop. Then, a second stimulus consisted on one of the other three haptic displays of the experiment: TFS, TRS and TRRS. At the end of each trial, users were asked to qualify the perception similarity between the stimuli presented in a Likert scale from 1 (completely different) to 7 (completely similar). These display methods were presented in a random order 10 times per approach, making a total of 30 trials.

4.3.4 Collected Data and Population

We collected data concerning the perceived similarity between the two stimuli presented on each trial. After completing the experiment, participants were asked to fill out a questionnaire that assessed their subjective opinion about any possible factor that

could have influenced their perception during the trials. The questions concerned the factors that could have helped the users to differentiate between the ground truth and the alternative haptic rendering techniques: did motion (**Q1**), curvature (**Q2**) and speed (**Q3**) helped you to differentiate the two stimuli? The questions were presented in a Likert scale answer format ranging from 1 (completely disagree) to 7 (completely agree). In the end, participants were asked to name another factor (if existed) that could have helped them to compare both stimuli. Twelve participants (3 females and 9 males, $M = 24.58$) took part in the experiment. Two of them were left-handed.

4.4 Results

4.4.1 Experiment

To study the perceived similarity between the different stimuli, we first analyzed the ratings for the answers concerning the comparisons between the GT and the three other haptic displays. We used a linear mixed model on the collected data to model the probability of perceived similarity with respect to the haptic display variable. The participants are considered as a random effect in the model. We performed an analysis of variance of the model, and we found a significant effect of the display ($F(2; 346) = 79 : 11, p < 0 : 001$). We performed a post-hoc analysis on the haptic displays using a Tukey test. Bonferroni correction was used for all post-hoc analyses. We found a significant difference between all the conditions: ENTROPiA ($TRSS, M = 4 : 39, SD = 1 : 72$) obtained higher ratings than TFS ($M = 2 : 79, SD = 1 : 55, Z = 9 : 01, p < 0 : 001$), and than RS ($M = 2 : 24, SD = 1 : 47, Z = 12 : 11, p < 0 : 001$). TFS was significantly rated higher than RS ($Z = 3 : 10, p = 0 : 006$). Participants responses are displayed in Figure 4.9.

4.4.2 Questionnaire

According to responses to **Q1**, participants considered that the sensation of motion was important for differentiating the two stimuli ($M = 5.666, SD = 1.874$). Results from **Q2** suggest that curvature was useful to differentiate the stimuli ($M = 4.75, SD = 1.712$). The answers from **Q3** demonstrated that the perceived speed was determinant for identifying differences between the ground truth and the alternative continuous surface rendering techniques ($M = 5.833, SD = 1.466$).

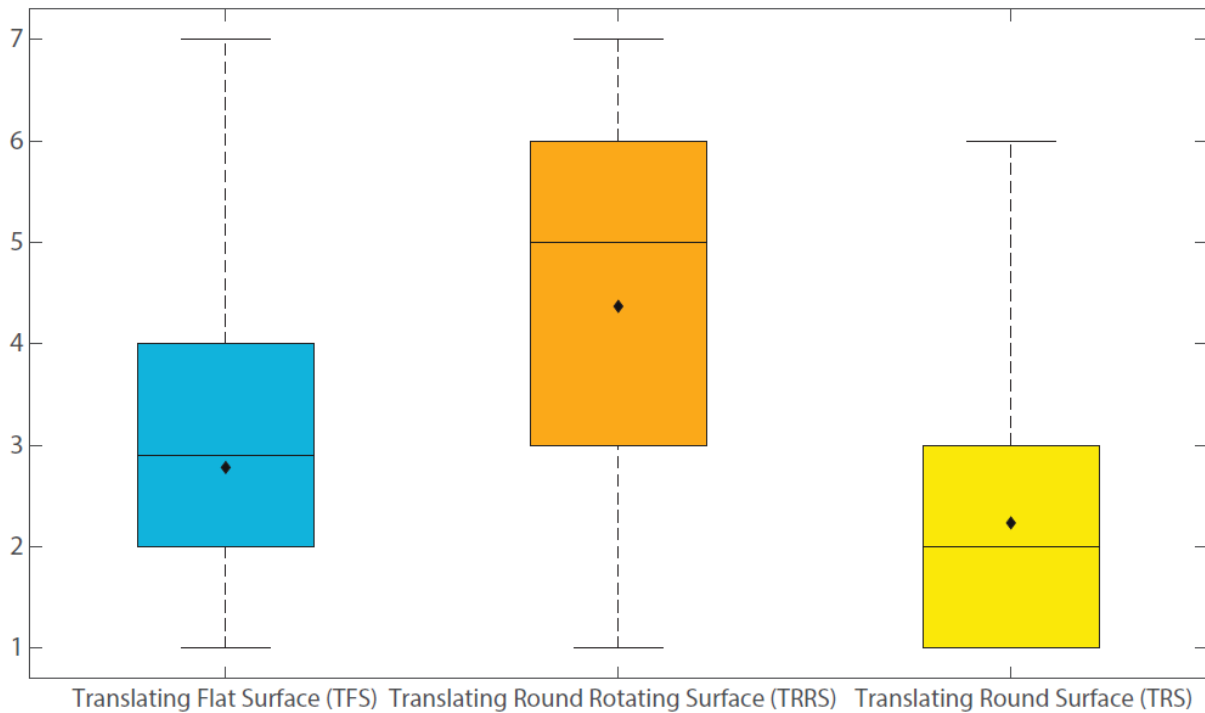


Figure 4.9 – Participant’s responses for assessing the similarity between touching the ground truth and the other three continuous contact rendering techniques. The round rotating surface was evaluated as the closest medium for providing a sensation closer to the ground truth.

4.5 Discussion

The design of ENTROPiA was conceived for addressing the necessity of having a free-hand haptic exploratory procedure that could not be limited to the display’s size and shape properties. In order to achieve this objective, we designed a rotating cylindrical prop that functions as an ETHD through an interaction technique that permits to explore a virtual surface coupling the prop’s rotation and position to provide the sense of touching a flat surface under the users’ fingers. A proof of concept and a user study were carried to test the integration of our approach in a VE and for testing its effectiveness at the moment of rendering haptic feedback. The proof of concept integrates different textures for flat surface rendering in a virtual simulation. The premise of the multi-sided surface display contributed by [2], [20] is retrieved in our approach by having an assortment of textures placed over the cylindrical prop’s curved surface. Integrating a texture that could cover the entire curved surface’s circumference could lead to an infinite surface rendering due to the surface’s geometrical properties.

The user study was elaborated to assess and compare users haptic perception between touching a flat surface and several approaches for rendering a similar sensation including our approach, one based on the state-of-the-art, and a mix of both. Results were in favor of our rotating prop approach as a means to render a sensation closer to touching the ground truth. Participants helped for determining important factors that influence shape perception. Speed, curvature and motion were the most influential factors for differentiating the sensation perceived by touching the ground truth and the other three conditions of the experiment. Two out of twelve participants mentioned that they perceived differences in the texture between the ground truth and the other conditions. The rest of the participants did not find any other factor beyond motion, curvature and speed that could have been useful for them to differentiate between the two stimuli.

The rotating surface approach has been undertaken in previous research works on haptics [67], [103]. However, these approaches as well as ENTROPiA come with limitations concerning the surface to be touched. The contact area was reduced to have a proper sensation of touching a flat surface. A bigger prop might imply a larger contact area yet the size might constraint the robot. Exploration in terms of influence of radius could determine if the aforementioned assumption is correct. The current implementation of this approach is also limited in the direction of haptic exploration. Further work could explore rendering curved surfaces, texture friction influence in haptic perception using our approach, as well as allowing multi-directional touch. The force exerted by participants when touching surfaces with the same properties such as ENTROPiA's has an influence on surface perception as suggested by Bettelani et al. [104]. The findings of this chapter could be further studied taking into account exerted force by participants in future work.

The design of the VE served to assign an application to our approach. Our proposed prop could hold even more textures depending on the interaction design of the environment where this approach could be integrated. With our approach, users can naturally explore a surface instead of being limited to the size of a prop's face or the resolution of a pin-array.

The optimal parameters of angular velocity and prop radius might vary from user to user. A personalized speed calibration session might be needed to find an optimal velocity for providing the sensation of touching a flat surface. Adapting a rotating round prop on a grounded ETHD provides the possibility of rendering a virtual surface while having a natural haptic exploratory procedure. Nevertheless, it could be also considered for other types of ETHDs. For instance, our approach could be incorporated into a mobile device as a means to have an unconstrained, continuous haptic feed which might become

considerably close to the ideal haptic device. Following the premises of the movable surface for rendering different volumes such as the work of Abtahi et al. [62], our approach does not need an active haptic display to render different volumes. Additionally, our approach could benefit from other contributions to the ETHD field. Including an omnidirectional platform approach by Vonach et al. [105] combined with the system setup proposed in this chapter could provide an immersive and realistic haptic experience. Integrating our approach to a UAV such as a drone could also be an alternative to move towards the infinite surface haptic display.

4.6 Conclusion

This chapter presented ENTROPiA: an approach for large, multi-texture rendering based on a cylindrical prop that displaces and rotates the prop below the user's finger to always provide a surface to be touched, giving the illusion of being in contact with a flat surface when following the prop's trajectory. This approach yields active surface rendering as users are exploring a large surface with their sense of touch in a VE. The rotating prop allowed to hold a set of different textures in it, and thus, it allowed rendering large, multi-textured surfaces.

ENTROPiA introduced a novel interaction technique for optimizing the size of a multi-textured surface display as well as the working area of a grounded ETHD-based system. A proof of concept ETHD was conceived to explore several virtual objects with different textures such as the case of a wooden desktop, a leather cover and a sheet of paper.

A user study was conducted to evaluate the haptic perception of virtual surfaces simulated by our approach. This user study prompted the participants to explore a large surface under different approaches: constantly touching a static curved surface, constantly touching a static flat surface, and the ENTROPiA approach. Participants responses were in favor of our approach as the means for rendering a sensation closer to the action of touching the ground truth.

This chapter showcased an approach that could be used to optimize surface rendering for ETHDs by profiting from the sensation given by coordinating the rotation and position of a cylindrical prop under the users' finger when exploring a large surface in an immersive VE.

ALLOWING OBJECT MANIPULATION WITH ETHDs

This chapter presents an approach for object manipulation using an ETHD. Named after the fictional butler from the Batman series, Alfred – “the haptic butler for VR” - is an approach based on an ETHD holding passive tangible objects that attach and detach from the robotic tray as needed (See Figure. 5.1), providing highly adaptable and faithful haptic rendering for manipulation and exploration of 3D objects in VR.

In addition, this approach permits to recreate the surface where the virtual object can be retrieved and left by the users. Our approach proposes an algorithm for pre-selecting the place where the user can retrieve or place the tangible element by taking into account the end-effector, the user’s hand, and the virtual object’s position; therefore optimizing the device’s placement.

In summary, the contributions presented in this chapter are the following:

- A novel surface display approach for object manipulation based on a robotic actuator capable of mapping a virtual object into a tangible object that can be detached and attached to the robot’s end-effector.
- An interaction technique for object selection, manipulation, and release.
- A set of illustrative scenarios that depict our approach’s key features.
- A speed performance evaluation for our approach carried out to estimate the delay when commanding the robot to go from one position to another.

This chapter presents a contribution to ETHDs **haptic feedback** and **actuator performance** by addressing the research questions related to object manipulation (RQ5) and control algorithm optimization (RQ6).

This chapter details the contribution’s components in the following sections. The approach, key features, and interaction technique are described in Section 5.1. The illustrative scenarios that showcase Alfred’s key features are presented in Section 5.2. The

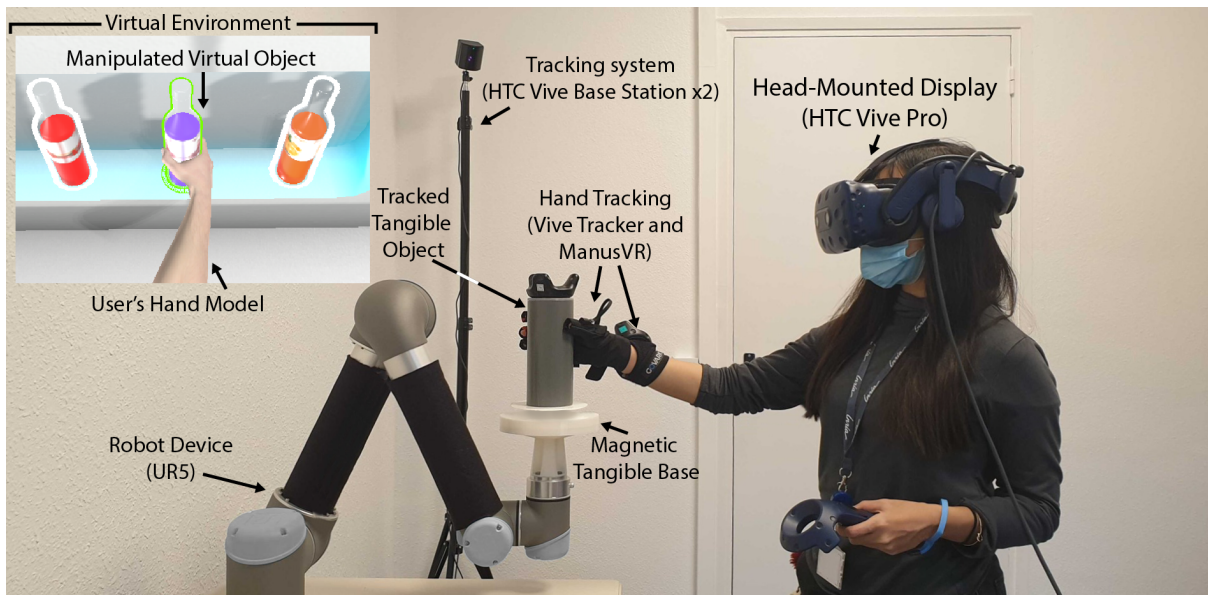


Figure 5.1 – The Alfred prototype: A user manipulates virtual objects by grasping and removing a tangible from the robotic tray. The Vive tracker mounted on the tangible allows precise reproduction of the tangible’s motions on the manipulated virtual object. Users wear an HTC Vive HMD displaying the virtual environment as shown in the upper left corner. A Vive tracker is strapped to the dorsal face of their hand equipped with a ManusVR tracking glove to precisely track and animate their virtual hand.

speed performance evaluation for Alfred is presented in Section 5.3. Results are presented in Section 5.4. A general discussion and conclusion are presented in Sections 5.5 and 5.6 respectively.

5.1 The ALFRED Approach

Without haptics, object manipulation in VR feels hollow and unreal, compromising user immersion and their feeling of presence in the VE. Alfred combines tangible objects and ETHDs in order to give users the illusion of a fully tangible virtual environment without compromising the VE’s malleability. It provides a high degree of freedom for VE reconfiguration while keeping the system’s complexity (hard- and software) manageable. The concept behind Alfred is that a set of detachable tangible proxies are held on a robotic manipulator which is capable of displacing and reorienting them in 3D to match the positions and orientations of corresponding virtual objects in an immersive 3D environment (see Fig. 5.2-A). Users begin by moving their hand in free space, while the system tries to

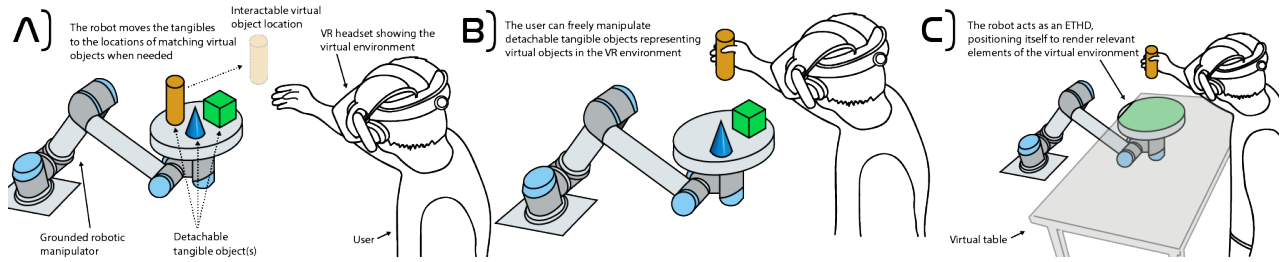


Figure 5.2 – Concept illustration for Alfred: (A) A robotic manipulator holds a set of tangible proxies capable of matching the properties of interactable virtual objects, placing them as required so they match the pose of virtual objects the users interact with. (B) Upon grasping, a tangible proxy detaches from the robot tray and becomes freely manipulable. (C) During manipulation, the robot tray acts as an ETHD, positioning itself to render portions of the VE, e.g. allowing the user to put down the manipulated object.

anticipate the possible physical interactions by placing tangible elements in the required locations. Since the tangible proxies are not permanently fixed to the robotic tray, users can freely manipulate them by picking them up (see Fig. 5.2-B). Haptic feedback during manipulation is provided by the physical prop, in an approach akin to passive haptics, while the robotic tray continues to act as an ETHD. During the manipulation phase, the robot anticipates further possible physical interactions between the manipulated object and the remainder of the VE. When the manipulated virtual object comes into contact with other parts of the virtual environment, the robotic tray is positioned such as to render reaction forces of the virtual environment onto the manipulated virtual object (see Figure 5.2-C). This allows users to e.g. place manipulated virtual objects on virtual surfaces such as tables as if they were truly present in the user’s physical environment.

Key features provided by Alfred are: (1) infinite re-spawn of virtual objects, (2) removal of virtual objects, (3) multiple virtual object mapping using only one physical proxy as long as their geometries are similar enough, and (4) free reconfiguration of the VE. These features are illustrated in the implementation of Alfred presented in Section 5.2.

This concept takes McNeely’s concept of "robotic shape displays" [12] one step further, making these objects detachable to allow free manipulation without the complexity of dealing with making the robotic manipulator transparent. Contrary to grounded [40], [106] or wearable [22] ETHDs with tangible objects as surface displays, our approach does not constrain manipulation to a limited subset of object grasp poses, allowing a wide range of natural manipulations of an object once grasped.

Also, Alfred decouples the actuation from the tangible object, setting it apart from

mobile robotic proxies [107], [108] which incorporate actuation inside tangible objects, as well as robotic manipulators with fixed tangible surface displays [106]. This feature also sets Alfred apart from the classic ETHD approach [106] in which the tangible is attached to the device’s end-effector when exploring the environment. In our contribution, the tangible only acts as a physical proxy for the virtual object, and the robotic manipulator repositions these proxies in the 3D environment. It therefore becomes possible to pick up and put down tangibles anywhere in the 3D environment, without any additional constraints regarding physically pairing the VE and the underlying physical environment. The only additional element occupying physical space is the robotic manipulator, which has the advantage of being mobile, allowing it to get out of the user’s way when necessary.

5.1.1 System components

Alfred builds on three sets of components: Physical components, components ensuring co-location between physical and virtual elements, and interaction components.

The physical components are responsible for providing the tangible representation of the VE. They encompass the robotic manipulator, which may be a robotic arm (as shown in Figure 5.2), the set of tangible objects, and a system for attaching and carrying the tangibles on the robot’s end-effector.

The robotic manipulator must be capable of moving the set of tangible objects to poses matching those of virtual objects. Consequently, its workspace should overlap with the region of the VE in which interaction and manipulation take place. Furthermore, its end-effector should have sufficient DoFs to match all possible positions and orientations of interactable virtual elements with those of the physical proxies. Finally, its actuation should allow it to carry the payload of physical proxies while ensuring sufficiently high accelerations and velocities to ensure the tangibles can be brought to target poses in a timely fashion.

The system for attaching the tangible objects to the robot’s end-effector should accommodate the required number of tangibles while ensuring that they are presented individually, avoiding unintended contact between the hand and other physical elements during the interaction. It should also secure the tangibles in place on the end-effector during relocation, while still allowing them to seamlessly detach upon grasping by the user.

Finally, the tangible objects must sufficiently match the shapes (and possibly other physical properties) of the virtual objects to be represented, or should implement solutions

for compensating mismatches (such as e.g. use of visual-haptic perceptual illusions [109], actuation for shape changing[110], augmentation with other haptic actuators [111]).

The second set of components is responsible for establishing and maintaining co-location between physical and virtual elements while avoiding discontinuities in virtual elements' poses. It encompasses registration, tracking and motion planning components.

Registration components ensure an initial match between the VE and the physical environment. This includes calibration of the user's hand model, of interactable virtual objects with respect to the tangibles, as well as of the robot's pose and motion with respect to the VE.

The tracking components include sensors and software for keeping track of the poses of the user and all physical elements to appropriately render their virtual counterparts. The tracking components' outputs also enable motion planning and provide input for the interaction components. To maintain coherence between user motor input and perceived visual and haptic feedback, tracking accuracy, low latency and high update rate are essential requirements. Furthermore, the software fusing input from multiple sensors must ensure continuity and coherence of the rendered virtual environment.

Motion planning software components are responsible for generating robot motion commands ensuring the tangibles are brought to the correct poses as precisely and as fast as possible. These commands must also ensure a match between the properties of the virtual objects' motions and the tangible objects' motions. Finally, these components are responsible for preventing unwanted contact between the user and the robot or tangibles.

The third set of components, i.e. interaction components, encompass the three components of a manipulation interaction technique as defined by Bowman et al. [112] (selection, manipulation, and release) as well as a pre-interaction component. The pre-interaction component fulfills the dual objective of making the user aware of interactable objects in the VE and of anticipating possible future selections, putting the system into an optimal state for responding to these selections. The selection component allows users to indicate to the system which virtual object they intend to interact with. This indication can be implicitly based on constraints in the interaction design and assumptions made based on user input, or may be explicitly provided through user input. The selection component also provides feedback indicating the feasibility and the success of a selection, e.g. through visual highlighting as discussed in Sec. 5.2.4. The manipulation component is based on ecological manipulation of a tangible object. Thus, it is restricted to the object being attached to the user's virtual hand and to the maintaining of the relation between the

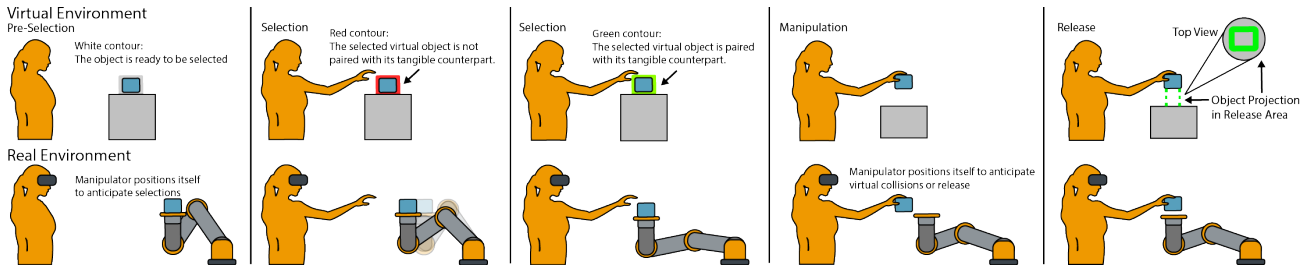


Figure 5.3 – Our implementation of Alfred’s interaction technique. Pre-selection: Selectable virtual objects show a white contour, the robot positions its end-effector to best anticipate future selections (see Figure 5.4). Selection: Objects are selected based on the distance of the hand to the virtual object. The selected object’s contour is red while Alfred has not aligned the tangible object with its virtual counterpart, and becomes green as soon as it has. Manipulation: The user freely manipulates the tangible object while the robot positions itself to anticipate collisions between object and environment. Release: Alfred’s end-effector encounters the tangible at a chosen release position.

tracked tangible’s pose and that of the virtual object. Faithful haptic feedback is implicitly provided through the use of tangible proxies. The release component allows users to indicate to the system which part of the VE the manipulated object will be released. This can be anticipated because of constraints to the interaction (e.g. as discussed in Sec. 5.2.4), can be inferred from user’s actions (see e.g. Sec. 5.2.5) or can be explicitly pointed out (see e.g. Sec. 5.2.3). This component provides feedback similarly to the selection component, indicating the feasibility and success of a release.

5.1.2 Safety

Safety is paramount in applications involving close collaboration between robotic arms and humans, especially in VR applications where the user is blind to the actual position and motion of the robotic arm. Safety in close human-robot collaboration has been extensively studied (e.g. [113]) and has been standardized for robotic manufacturing in [114].

Implementations of Alfred should consider these requirements and ensure multiple levels of safety in their physical, co-location, and interaction components to prevent any potential harm to the user such as e.g.: (1) Use of a robotic manipulator with inherent compliance and passive safety through low weights, inertia and speeds; (2) Reliable high frequency and minimal latency tracking and associated collision avoidance algorithms; (3) Dead-man switches, emergency stops, and external supervision; (4) Interaction techniques warning users of potentially dangerous situations.

5.2 Illustrative Setup

To illustrate the concept described in Section 5.1, we designed a simplified prototype of Alfred integrating the three sets of system components and illustrating its key features through several illustrative manipulation scenarios. We chose to restrict the scope of interactions to (1) the use of a single tangible prop and (2) virtual objects in co-planar arrangements.

5.2.1 System prototype

In terms of physical components, the set-up (shown in Fig. 5.1) used a UR5 robot equipped with a 3D-printed end-effector acting as a tray for a single cylindrical tangible object. The tangible is held in place using passive magnets embedded within its base and the tray, similarly to methods used in [109] and [115]. To ensure co-location, the tangible object is tracked using a Vive tracker, ensuring accurate reflection of manipulation movements onto the corresponding virtual object. The VE is displayed through an HTC Vive HMD, and the users' right hand is tracked using a Vive tracker and a ManusVR glove, allowing precise animation of their virtual hand.

5.2.2 Interaction Technique

As previously mentioned in Section 5.1.1, this Alfred prototype proposes an interaction technique based on three interaction phases in addition to the pre-interaction phase (see Figure 5.3), during which interactable objects are highlighted with a glowing white contour when the hand is close to them:

Selection Object selection can be either constrained, in the case where there is only one interactable virtual object in the VE (see Section 5.2.3), or unconstrained if multiple virtual objects can be selected (see Sections 5.2.4 and 5.2.5). It can also occur explicitly (see Section 5.2.3) or implicitly e.g. by considering the distance between the virtual hand and closest virtual object (see Sections 5.2.4 and 5.2.5). If the user moves to grasp or touch a selected object before it has been brought into position by the robot, the contour becomes red, otherwise, it becomes green as soon as the tangible is in position, signaling to the user that physical interaction is now possible (see Figures 5.3).

Manipulation Users can then freely touch, grasp and pick up the virtual object. In the latter case, the virtual model of the manipulated object is moved in the VE based on information from the tracker mounted on the tangible prop (see Fig. 5.1).

Release Users explicitly (see Sections 5.2.3) or implicitly (see Sections 5.2.4, and 5.2.5) select the place where they can release the object. A color-coded circular highlight indicates the release position and the feasibility of a release by switching from red (see Figure 5.5) to green (see Figure 5.7).

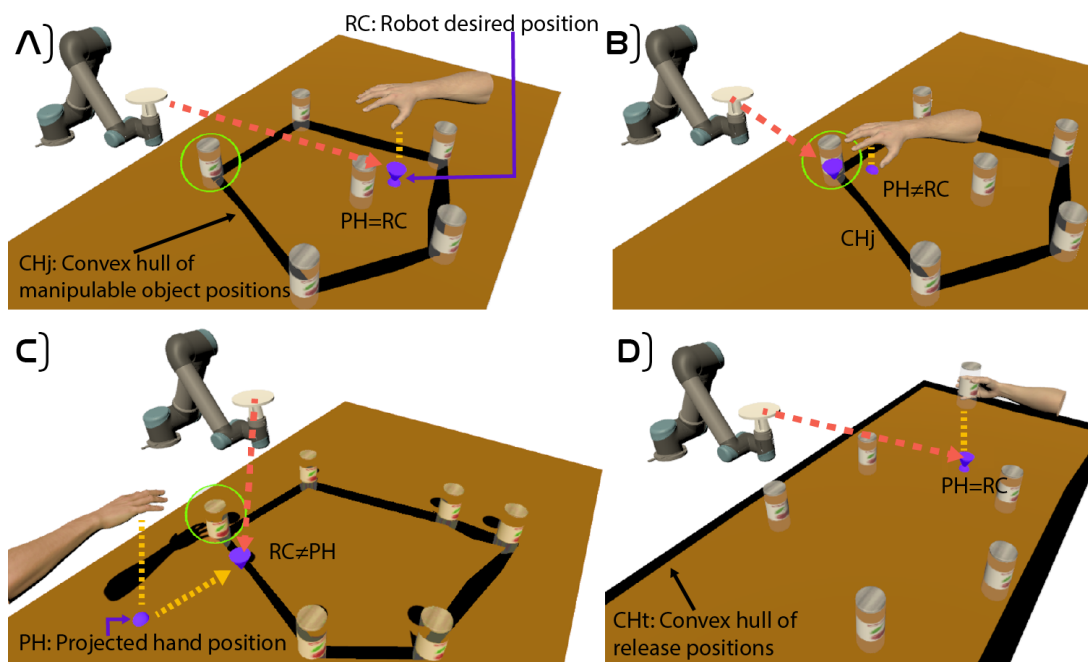


Figure 5.4 – Computation of the robot surface display desired position (RC) when grasping and release positions are not known beforehand: When the user has no object in hand (cases A, B & C), the robot motion space is the inside of the convex hull CHj formed by the object center positions in the plane supporting the objects, a table in this example. The user’s hand position is projected in this plane (PH), if PH is within CHj (cases A & B), PH is used as the robot surface display’s position command (case A) unless the hand is close enough to an object (case B) in which case the robot desired position becomes that of said object. If PH lies outside CHj (case C), RC is computed as the point of CHj closest to PH. Similarly, once the user has an object in hand (case D), the robot motion space is delineated by CHt, formed here by the four corners of the virtual table. RC is then computed based on PH, identically to cases A or C, depending on whether the hand is directly above the table or not. The release position is freely chosen within CHt by the user, and the convex hull CHj is recomputed upon release of the object.

In this implementation, trajectory planning for the UR5 is kept simple: At every frame, the robot surface display's desired position (RC) is computed within a restricted interaction zone (see e.g. Figure 5.4) based on the interaction phase, the user's hand position and the position of interactable virtual objects. Once RC is known, the surface display trajectory is computed to achieve a linear motion of the robot's surface display towards RC, using the Universal Robots' SDK.

5.2.3 Illustration 1: Manipulating one object between known positions



Figure 5.5 – Users face a table onto which a virtual part is extruded. They can pick it up and inspect it, then they select whether the part is flawed or good. This explicitly indicates their future to place the part either into the disposal bin or onto the conveyor belt. The robot drives to the chosen release position to preempt the user's release of the part, after which it removes the tangible object from the interaction space as the virtual part is either destroyed or removed from the scene.

This first scenario is a virtual parts inspection task on an assembly line described in Figure 5.5. It showcases the possibility for infinitely spawning virtual objects which will always have an existing physical counterpart, as well as the possibility for removing virtual objects from the environment without leaving problematic physical objects in the supposedly empty virtual interaction space. This scenario constrains interactions by providing a single initial object position, and two possible fixed object destinations (the disposal bin and the conveyor belt for the good parts). Combined with the user's explicit indication of a future release position, this scenario uses a control scheme in which the

robot carrying the tangible is initially driven to the location where the virtual part is extruded (i.e. initial position), then drives to the release position indicated by the user. Finally, the robot removes the tangible from the interaction space once the virtual part is either destroyed or removed. This scenario represents the most favorable configuration for the robot’s control, as only one tangible object is used at a time and the robot end-effector’s target location is known beforehand. However, this comes at the expense of a limited range of possible interactions, and cannot adequately respond to the user performing unpredictable releases.

5.2.4 Illustration 2: Mapping one tangible to many virtual objects



Figure 5.6 – Users embody a virtual bartender mixing virtual cocktails. They select one of six bottles arranged on the bar’s shelf, which they manipulate to pour drinks, before placing them back at their original position.

This scenario showcases how Alfred allows mapping of a single tangible object to multiple simultaneously present virtual counterparts by letting a user manipulate one of many different virtual bottles in a bartending scenario (see Figure 5.6). To allow this, we introduce additions to both the robot control and interaction technique. Regarding the control of the robot, since the tangible object can be mapped to virtual objects at different locations, the robotic arm has to anticipate the users’ actions in order to ensure that the tangible object is placed at the desired location. In this sense, the robot behaves like a traditional ETHD. The user’s hand position is projected onto the line passing through the centers of the virtual bottle bases, indicating the desired robot surface display position. The surface display follows the user’s hand motion while remaining constrained to this

line segment in the plane on which all virtual bottles are placed. This behavior ensures the robot always has the shortest distance to travel to the position of any bottle the user chooses to interact with. However, this robot control approach by itself runs the risk of introducing unwanted motions to the prop and positional mismatches if the user goes to rapidly grasp a bottle. The interaction technique is therefore improved by defining a selection region defined around each virtual bottle. If the user's hand comes within this region, it is assumed the user will grasp the associated bottle (selection) and the robot is immediately driven to the location where the tangible prop matches the bottle's pose. Furthermore, users always return bottles they pick up to the same location. The release position is implicitly defined at the moment of grasping, and the robot does not need to follow the user's motion during the free manipulation phase. It simply remains in position until the user puts the virtual bottle back. However, this approach where the release position is known in advance could easily be extended to releases at a different position.

5.2.5 Illustration 3: Freely manipulating one of many objects



Figure 5.7 – Unconstrained manipulation of multiple objects. In this scenario, the user faces a table holding five jars in arbitrary locations. Users are free to pick up any jar, manipulate it and place it back wherever they please, which includes stacking jars on top of each other.

This final scenario explores the use of Alfred for unconstrained manipulation of one of many virtual objects (see Figure 5.7). Similarly to the previous scenario, a single tangible prop is mapped to multiple manipulable virtual objects. However, in this case the robot has to act as an ETHD during the free interaction phase, representing any surface or object in the environment that the manipulated object may come into contact with. Since only very few assumptions can be made about the user's intent and the interaction is

unconstrained, this scenario showcases the most complex variant of control algorithm for the robot surface display’s desired position. If the robot followed the user’s hand anywhere in the workspace, this could potentially bring the robot very far from the virtual objects to be represented, unnecessarily delaying subsequent interactions. Figure 5.4 details the approach for calculating the robot surface display’s desired position in order to avoid this. In the event that a user wishes to grab a jar in a stack of jars, the height of the user’s hand above the table is used to define whether the robot desired position is within the table plane (user wishes to grab the lower jar in the stack) or above the table plane (user wishes to grab one of the top jars in the stack).

5.3 Evaluation

The main criterion for the quality of haptic rendering using our system is the ability for the system to adequately anticipate contact between a user and a virtual object. Correct timing is essential to ensure that the tangible prop and end-effector are in position before the user’s hand comes into contact with the virtual element to be represented. The capability for an implementation of Alfred to comply with this timing constraint depends on numerous factors, including the robot’s dynamics, the size of the workspace, the VE configuration and complexity, the robot control scheme, and interaction technique (see Section 5.2) as well as the user’s movement speeds.

Considering Covid-19 restrictions, we performed an evaluation of the system’s rendering latency based on simulated robot motions computed from separately recorded user hand movements.

Five participants (4 male, 1 female, ages 24-33, all right-handed) recorded planar radial movements when moving from a fixed start position P_{start} towards end positions P_{target} , and back (see Figure 5.8), performing 3 repetitions of each motion.

The users’ hands were tracked using an HTC Vive tracker providing position and orientation at a frame-rate of 90Hz.

Recorded motions were then fed into a simulation of the robot (URSim running at a frame-rate of 125Hz), providing reference values for computing robot motions. Four different schemes for the end-effector’s position control were considered:

- Snapping (SP): the robot’s end-effector is driven to P_{target} , independently of the user’s hand position (as is the case in our first scenario discussed in Section 5.2.3). This scheme is inspired by the proposition made by Yokokohji et al. [14] which

suggested the use of snapping regions so the robot could get to that point. The simulation presented to the experts presented in Chapter 2 follows this approach.

- Following (FW): the projection of the hand position onto the axis connecting P_{start} and P_{target} is set as the end-effector’s desired position. This approach is the simplest implementation of ETHD behavior. This control scheme has been used in works such as the one proposed by Bouzbib et al [59]. The control scheme for the “Follow” technique presented in Chapter 3 used this approach for placing the robot’s end-effector below the users’ hands.
- Snap After Threshold (ST): the robot is driven to P_{target} after the user’s hand crosses a threshold defined as the midpoint between P_{start} and P_{target} . This approach showcases behavior as it would occur in the case of distance-based selection of virtual objects. This control scheme combines the control approach by Yokokohji et al [1] and the notion of establishing a threshold based on the hand’s distance. This approach has been used in works such as Posselt et al. [2].
- Snap After Follow (SF): this control scheme is a hybrid between the two aforementioned approaches. The end-effector follows the projection of the user’s hand. Once the hand crosses the threshold (midpoint between P_{start} and P_{target}), the end-effector drives directly to P_{target} , independently of the user’s hand position. This control scheme is implemented in both scenarios described in Sections 5.2.4 and 5.2.5.

The simulator implemented realistic robot dynamics, considering an end-effector payload of 0.5kg, and the robot’s controller tuned to act as a critically damped system. We obtained 4 robot motion recordings and 1 hand motion recording for each trial, from which we computed the hand and robot’s respective arrival times at the target. Data for each distance and orientation pair were averaged over the 3 trial blocks for each user, yielding one point estimate per condition. Since no significant influence of orientation on hand arrival times was observed (pairwise Student’s t-tests do not reject H_0 at $\alpha = 0.05$), we considered trials at different orientations as repeats of trials at a given distance and computed the mean hand and robot arrival times as a function of target distance. The results are shown in Figure 5.9. The recorded user motions are intended to provide orders of magnitudes of Alfred’s performance and are in no way meant to be exhaustive or fully representative.

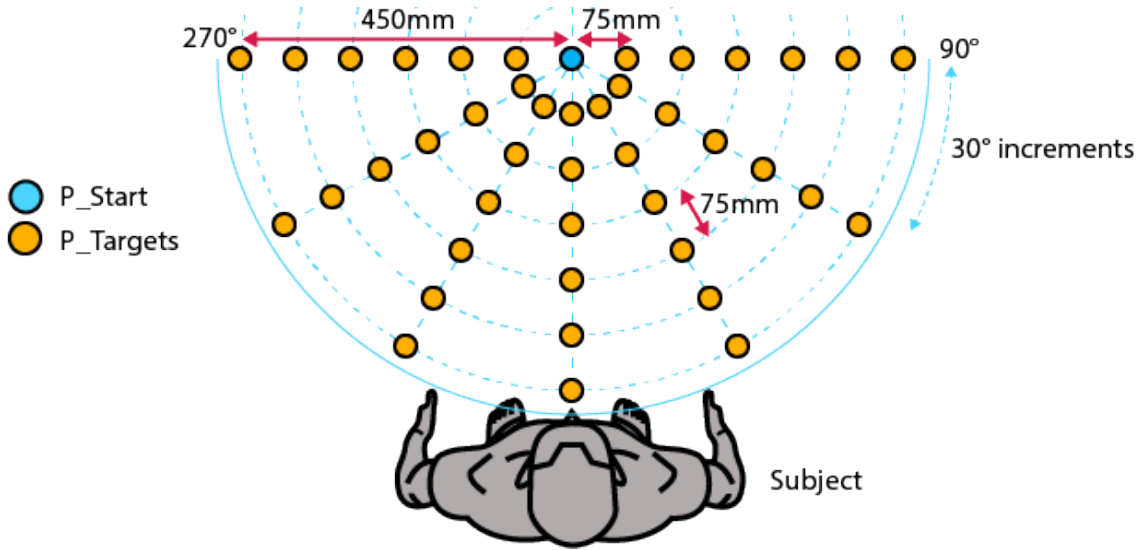


Figure 5.8 – Recorded user motions covered 6 distances between P_{start} (blue) and P_{target} (yellow) in 75mm increments over a range of 450mm (i.e. the full radius of the UR5’s workspace) for 7 directions, in 30° increments over a range of 180°.

5.4 Results

We obtained task completion times (i.e. times for the hand or robot to reach a target at a given distance) for the hand and the robot under each of the four considered control schemes (see Figure 5.9) from which we inferred delay times for each control scheme, i.e. the difference in arrival times between the hand and robot in a given control scheme.

The overall average delay times for all conditions ranged approximately between 2.1s and 3.6s. The average task completion time for users varied between 0.42s and 1.24s, with mean performances across subjects as follows: 75mm $M = 0.63s$, 150mm $M = 0.8s$, 225mm $M = 0.78s$, 300mm $M = 0.8s$, 375mm $M = 0.93s$, 450mm $M = 1.04s$.

The results show that the SP position control provides the most reactive robot control for all distances (75mm $M = 2.87s$, 150mm $M = 3.37s$, 225mm $M = 3.69s$, 300mm $M = 3.89s$, 375mm $M = 3.88s$, 450mm $M = 3.18s$). Pairwise Student t-tests between condition within distances show the observed differences are significant at $\alpha = 0.05$, except for the difference between SP and FW at 150mm.

The longest times to arrive to the target were obtained when using the ST control scheme (75mm $M = 3.5s$, 150mm $M = 4.07s$, 225mm $M = 4.27s$, 300mm $M = 4.41s$, 375mm $M = 4.47s$, 450mm $M = 3.84s$). Student t-tests between condition within distances show observed differences are significant at $\alpha = 0.05$, except for the difference

between ST and FW at 450mm.

The FW control scheme (75mm $M = 3.11s$, 150mm $M = 3.63s$, 225mm $M = 3.83s$, 300mm $M = 4.01s$, 375mm $M = 4s$, 450mm $M = 3.76s$) and SF control scheme (75mm $M = 3.06s$, 150mm $M = 3.59s$, 225mm $M = 3.83s$, 300mm $M = 4.01s$, 375mm $M = 4.02s$, 450mm $M = 3.57s$) yielded similar results for all distances.

For all control schemes, the difference in arrival times between hand and robot (i.e. the delay) increased with the length of motion, up to 375mm. Above this distance, the delay begins to drop, with the largest motions (450 mm) yielding the smallest measured delay for all the control schemes except FW (differences in delays between distances, within control schemes are significant at $\alpha = 0.05$ except for FW - Pairwise Student's t-tests).

5.5 Discussion

In this chapter we propose Alfred, a hybrid approach that exploits the benefits of passive haptics and ETHDs. By remapping tangible objects to virtual objects, Alfred provides key features such as: infinite re-spawn and removal of virtual objects, multiple virtual object mapping to a single tangible, and tangible elements' reconfiguration in an immersive environment in VR. We implemented a prototype and 3 illustrative scenarios that portray how Alfred successfully provides haptic feedback in malleable VEs.

To evaluate this approach's performance, we simulated Alfred's behavior for four representative robot control schemes. The results indicate that a snapping control scheme performs best on average. These results were expected since the robot is prompted to go directly to the target rather than responding to a user's motions.

Following (FW) and threshold-based (ST, SF) approaches performed similarly well. The reason for SF performing worse than SP might be related to the robot's positional error being relatively small at the beginning of the movement for snapping after following when compared to snapping alone, which would mean lower robot speeds during motion. We considered the integration of real-time hand following in the control schemes to see if the robot's performance was faster under this condition. Snap After Threshold (ST) performed worst, which was expected since the robot has to wait until the hand position crosses a threshold to begin moving to the target position. In real-life scenarios in which the users' intent cannot be predicted, following approaches appear as the best choice considering the small differences concerning the performances obtained with snapping.

The advantages of the detachable tangible approach poses the challenge of properly

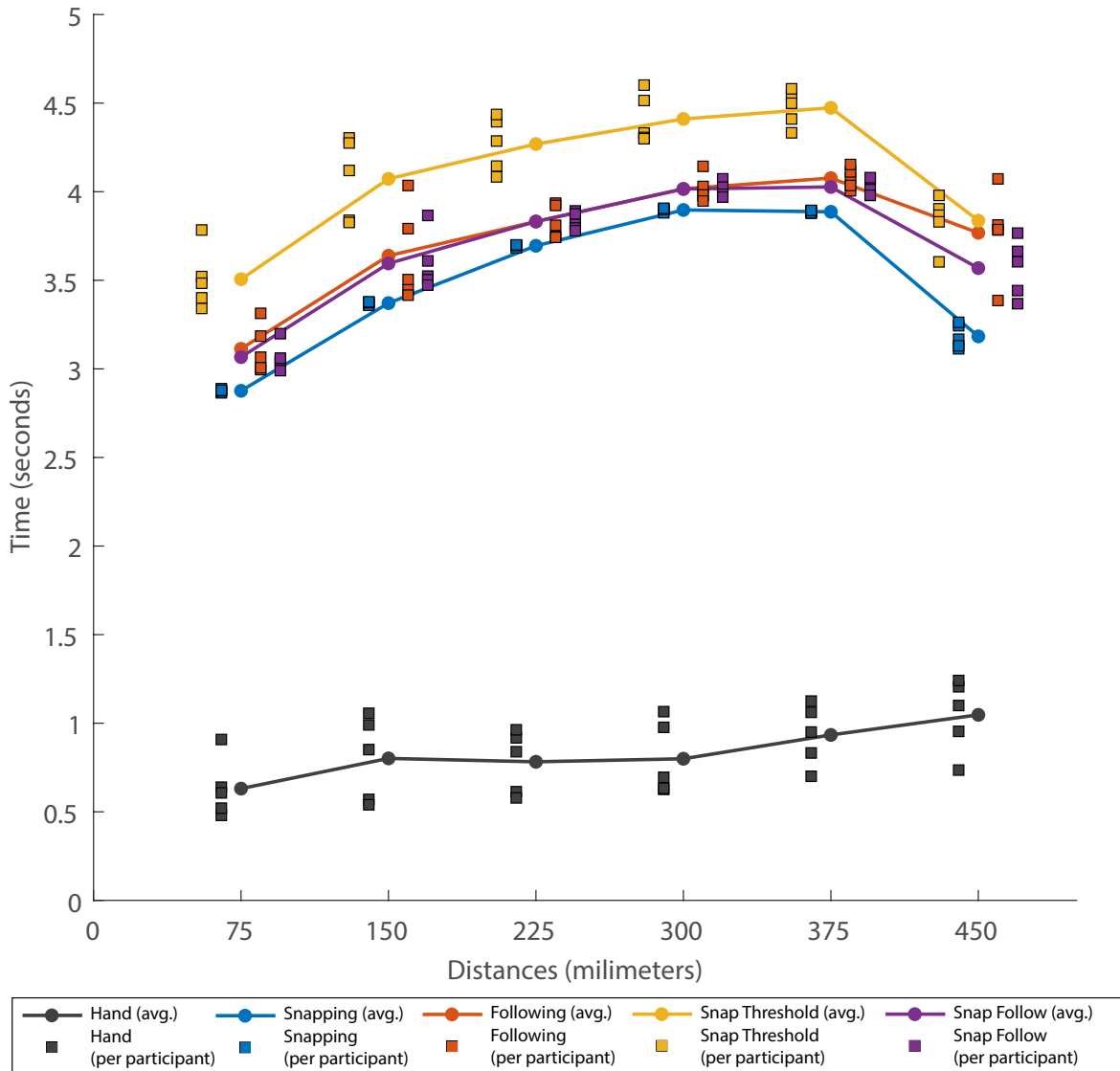


Figure 5.9 – Average time to reach the target position for the users’ hand and robot end-effector under the 4 control schemes considered. The mean times for each motion distance are shown with a square symbol. The overall average for the hand motions and robot motions under each control scheme is plotted as a line showing the arrival time as a function of distance to the target.

tracking the object without compromising manipulation. In our current implementation, the tracker attached to the top of the tangible may hinder some object manipulations, thus future work will include improving tracking hardware to make it unobtrusive (e.g. using ArUco markers [116]).

Latency is still a challenge to be addressed by the ETHD research community. The

delay for arriving at the target is a compound measure of human behavior and associated robot behavior and can thus be addressed through improvements to the robot hardware and control as well as through developed interaction techniques. Alfred could benefit from the integration of complementary approaches from the state of the art such as haptic-retargeting [117] to address speed and latency issues. Interestingly, the robot's performance for larger distances (450 mm) seems to be as fast as the one for shorter distances (75 mm). This could be due to the time the robot has to properly calculate and optimize its trajectory for avoiding overshooting with the current control parameters.

Increasing the robot velocity would also require taking into account more stringent safety measures to avoid unwanted collisions with the user. For the moment our approach addresses these issues through constraints to the robot's motion space and the designed interaction technique which informs users about the availability of tangible objects for manipulation. In parallel, it will be of interest to experimentally evaluate the impact of system delays for different interaction techniques on user experience and immersion.

5.6 Conclusion

This chapter presented "Alfred", a novel approach for object manipulation in 3D immersive VR. Alfred uses a robotic manipulator to move tangible objects in its workspace such that they match the pose of virtual objects to be interacted with. Users can then naturally touch, grasp, and manipulate a virtual object while feeling congruent and realistic haptic feedback from the tangible proxy. The tangible proxy can detach from the robot, allowing natural and unconstrained manipulation in the 3D VE.

Alfred included an interaction technique that permitted users to select, manipulate, and release objects in a VE. This interaction technique was complemented with an algorithm that optimized the device's movement when users selected or released an object in the VE. Additionally, this chapter presented three illustrative scenarios which were conceived to show Alfred's main key features: (1) An industrial assembly line scenario that allowed infinite re-spawn and removal of virtual objects, (2) A virtual bar that allowed multiple virtual object mapping using only one physical proxy, and (3) a jar-stacking scenario that allowed free reconfiguration of multiple tangible elements in the VE.

Alfred was evaluated under four control schemes that aimed to optimize the device positioning when users selected an object for manipulation. Results from this evaluation suggest that continuously following the users' hands and snapping to the target position

could be approached to optimize our approach's object rendering.

This chapter showcased that Alfred could be adapted to a wide range of VEs and interaction scenarios. Thus, making it a promising approach for object manipulation in VR using an ETHD.

CONCLUSION

This thesis presented a series of contributions to leverage the state of encountered-type haptic displays primarily on the **usability** and **haptic feedback** research axes.

6.1 Contributions

Chapter 1 presented a literature review about ETHDs. This chapter proposed a definition of the term encountered-type haptic displays and its fundamental notions. Later, the history of ETHDs was presented to showcase how the field has evolved over the years. This chapter also contributed with a taxonomy for classifying ETHDs according to their actuator type. Then, a hardware review was presented where the research works were classified according to the actuator types, surface displays, tracking systems, and visual display devices. Later, the research works were reviewed according to the type of haptic feedback, interaction, and application. This chapter concluded by raising the research questions to be answered in this thesis based on the ETHD field's limitations and research opportunities.

Chapter 2 presented the design of safety techniques that seek to balance users' immersion and perceived safety when interacting with an ETHD. The chapter introduced a design space dedicated to creating safety techniques based on visual feedback to warn the users about the display's actions and state. A set of techniques were created from the design space to explore the different possibilities of visual feedback for avoiding collisions with the occluded haptic display. Later, a preliminary evaluation was carried out with a group of experts in haptics, VR, and ETHDs to reflect and propose a set of criteria to evaluate the safety techniques taking into account users' perceived safety and immersion. Then the chapter presented the results of the evaluation made by these experts under the criteria they previously proposed. Overall, results from this evaluation suggest that the higher the immersion level, the higher the level of users' perceived safety.

Chapter 3 studied the design and evaluation of interaction techniques for ETHDs.

First, a design space for interaction techniques was presented along with its main features: input, movement control, and contact. Later, the chapter presented a set of interaction techniques conceived from the aforementioned design space. A use-case scenario based on finger painting was created to contextualize the use of the techniques. Later, the techniques were evaluated in a user study to assess user experience and their performance in helping users to accomplish the coloring task. Results suggested that the Clutch and Drag techniques could be useful for a scenario that requires large surface exploration in a finger painting task. The designed techniques could be used in other application scenarios and contexts where other types of applications might be required.

Chapter 4 presented ENTROPiA: Encountered-Type Rotating Prop Approach. This approach is based on a round surface display that spins in synchrony with the users' finger displacement to give users the sensation of touching a large surface in a virtual environment. This approach was envisioned to optimize the size of the surface display and the area it renders. Results from the carried user study suggest that this approach could serve as an alternative for rendering large surfaces using an ETHD.

Chapter 5 introduced Alfred, the haptic butler: an approach for object manipulation using an ETHD. This approach consists of a tangible object that can be detached from the ETHD's end-effector to be independently manipulated. Alfred includes an interaction technique for object selection, manipulation, and release. This technique uses a control algorithm that permitted to optimize the object's selection based on the users' hand and device's end-effector position. Alfred's key features were portrayed in three illustrative scenarios that allowed users to create, destroy, and re-map virtual objects in VR and therefore, to reconfigure the virtual environment.

6.2 Perspectives

6.2.1 Short Term Perspectives

The presented contributions in this thesis could be further augmented in the short term by future work focused on key areas.

In the case of addressing user safety presented in Chapter 2, multi-modal feedback (such as auditory or complimentary haptic feedback) can be considered for signaling users the proximity of the occluded ETHD. In addition, the proposed design space for conceiving safety techniques can be further explored and expanded to adapt the techniques

to the growing diversity of application domains for ETHDs. Visual feedback could also be adapted to other types of visual display devices, primarily those using AR and MR. Research could look for visual displays that adapt to the fact that users see superposed virtual elements that might occlude or not the ETHD in a given application.

The interaction techniques conceived and presented in Chapter 3 could be adapted to other types of actuators and shape displays. Additionally, the design space dedicated to surface exploration can be further expanded in its branches and feature combinations. However, the design space could also be enlarged to consider other features that go beyond the scope of the presented contribution. Future work on interaction techniques could also focus on conceiving specialized techniques for the growing assortment of shape displays for ETHDs. This research direction could also look for an interaction technique that could be generalized for all types of ETHD actuators.

The approach introduced for large surface rendering in Chapter 4 can be integrated into other types of actuators. This approach could be further exploited by ungrounded actuators to overcome the limitations of grounded actuators in terms of workspace. Future research could look for optimizing the shape display for providing a larger, unconstrained contact area that users could touch with their hand palm. Large surface rendering could go towards the implementation of the infinite surface haptic displays, which is a milestone to be achieved before Sutherland's ultimate display [118].

Future work for object manipulation presented in Chapter 5 could consider the integration of a surface display that could present a gallery of tangible objects with different geometry as a means to recreate a wider number of objects that could be manipulated in a virtual environment. The grasping sensation could be further enhanced with the use of visuo-haptic illusions such as the case of [109]. The proposed approach in this chapter can be further evaluated with users to assess if they feel a difference between the approach and a ground truth condition based on passive haptics.

6.2.2 Long-Term Perspectives

The research work presented in this thesis opens up perspectives for future work in the long term. Before sharing my ideas, I invite you to consider first that the concept of ETHDs is a step towards the ultimate display first imagined by Sutherland [118]. Based on this premise, research for ETHDs could continue evolving for bringing up more sophisticated ways of rendering haptic feedback.

Long-term research paths could further study interaction techniques for ETHDs, ac-

tuator diversification, advanced surface display development, and the adaptation to new visualization technologies.

Research in interaction techniques for ETHDs could leverage the current existing devices' capabilities for rendering haptic feedback. For instance, research could conceive interaction techniques dedicated to object selection and manipulation with ETHDs under different actuator types. The integration of multiple users would require new interaction techniques that allow an intuitive multiple-user interaction with one or even multiple ETHDs.

The actuator technologies that ETHDs use currently could be optimized and enhanced for all the different types. Research for each ETHD actuator type could be focused on leveraging their strengths. Grounded ETHDs could benefit from their anchor to the ground to further expand their possibilities for rendering force feedback. Ungrounded ETHDs on the other hand, could continue exploiting their "unlimited" workspace for tasks that involve navigation in VEs. Wearable ETHDs could continue evolving for bringing up a wider assortment of tangible elements that could recreate different objects with different geometries.

Research could explore new ways to render more complex surfaces using ETHDs. We are now witnessing how surface displays are being optimized to always render a surface as long as the user is in contact with it as we have seen in [19]. An unconstrained workspace coming from an ungrounded ETHD, coupled with a surface display that can optimize surface rendering could render a significantly larger area compared to the one rendered by nowadays approaches. Advancements in surface displays could lead to surfaces that dynamically adapt to the contexts and shapes they represent in a VE. Approaches for object manipulation such as the one presented in Chapter 5 could be integrated into ungrounded ETHDs for rendering graspable objects in a larger, unconstrained workspace. Future work could consider the use of multiple, interchangeable surface displays such as the approach presented by [119]. The ETHD could select surface displays that could represent either a surface or an object that users could touch and manipulate.

The crescent interest in visualization technologies such as AR and MR poses a challenge for ETHDs since these technologies mix elements of the real and virtual environments. Research could look for strategies to hide the ETHDs actuators while displaying a large part of the real environment.

All of these advancements could help ETHDs to move towards their integration into the ultimate display that could render an alternative (and virtual) reality with all the

sensory stimulation that happens in real life. These advancements should be done by taking into account human factors that help ETHDs to be integrated into daily-life use contexts.

Epilogue

Research nowadays and tomorrow should take into account both human and technological factors if we intend for technologies such as ETHDs to be adopted in a wider range of applications. Technology should not be augmented only for the sake of augmenting; there should be real problems and necessities that require our technical contributions. I sincerely hope this thesis has contributed to that purpose.

AUTHOR'S PUBLICATIONS

A.1 Peer-Reviewed Journals

- **V.R. Mercado**, M. Marchal, and A. Lécuyer. ENTROPiA: Towards Infinite Surface Haptic Displays in Virtual Reality Using Encountered-Type Rotating Props. In *IEEE Transactions on Visualization and Computer Graphics*, Volume 27, Issue 3, pages 2237 - 2243, 2021
- **V.R. Mercado**, M. Marchal, and A. Lécuyer. "Haptics On-Demand": A Survey on Encountered-Type Haptic Displays. In *IEEE Transactions on Haptics*, Volume 14, Issue 3, pages 449 - 464, 2021

A.2 Peer-Reviewed Conferences

- **V.R. Mercado**, T. Howard, H. Si-Mohammed, F. Argelaguet, and A. Lécuyer. Alfred: the Haptic Butler On-Demand Tangibles for Object Manipulation in Virtual Reality using an ETHDs. In *Proc. of IEEE World Haptics Conference (WHC)*, pages 373 - 378, 2021
- **V.R. Mercado**, M. Marchal, and A. Lécuyer. Design and Evaluation of Interaction Techniques Dedicated to Integrate Encountered-Type Haptic Displays in Virtual Environments. In *Proc. of IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pages 230 - 238, 2021

A.3 In Preparation

- **V.R. Mercado**, F. Argelaguet, G. Casiez, and A. Lécuyer. Watch out for the Robot! Designing Visual Feedback Safety Techniques when Interacting with Encountered-

Type Haptic Displays. *Submitted to ACM Conference on Human Factors in Computing Systems (CHI). (In Review).*

- J. Cauquis, **V.R. Mercado**, Jean-Marie Normand, Géry Casiez, and Anatole Lécuyer. *In Preparation.*

A.4 Miscellaneous

- **V.R. Mercado**, JM. Normand, and A. Lécuyer. “Kapow!": Augmenting Contacts with Real and Virtual Objects Using Stylized Visual Effects. In *Proc. of IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct)*. 116-117., 2020.
- A. Audinot, D. Dewez, G. Fouché, R. Fribourg, T. Howard, F. Lécuyer, T. Luong, **V.R. Mercado**, A. Reuzeau, T. Rinnert, G. Vailland, and F. Argelaguet. 3Dexterity: Finding your place in a 3-armed world. In *Proc. of IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*. 521-522., 2020.
- H. Brument, R. Fribourg, G. Gallagher, T. Howard, F. Lécuyer, T. Luong, **V.R. Mercado**, E. Peillard, X. de Tinguy, and M. Marchal. Pyramid Escape: Design of Novel Passive Haptics Interactions for an Immersive and Modular Scenario. In *Proc. of IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. 1409-1410., 2019.

RÉSUMÉ ÉTENDU EN FRANÇAIS

Les technologies de réalité virtuelle (RV) nous permettent d'être sous l'immersion dans des mondes virtuels envoûtants. Tandis que les technologies haptiques issues de la robotique ont permis d'accroître l'immersion dans ces mondes virtuels en y apportant la sensation du toucher. Des années de recherche sur l'haptique, la robotique et les interaction RV ont conduit au développement d'une catégorie de dispositifs appelés interfaces à contact intermittent (ICI). Les ICI permettent aux utilisateurs de toucher des surfaces dans un environnement virtuel (EV) en plaçant une surface tangible de sorte à ce que les utilisateurs puissent volontairement la toucher aussi naturellement qu'ils le feraient dans un environnement réel.

Cette thèse, intitulée **Contribution à l'utilisabilité et au retour haptique des interfaces à contact intermittent**, présente une série de travaux de recherche visant à améliorer des capacités d'utilisation et du retour haptique des ICI. Nous avons cherché à répondre aux limitations actuelles de ces interfaces haptiques en concevant des techniques d'interaction qui augmentent l'utilisabilité du système et en concevant de nouveaux paradigmes de retour haptique pour augmenter les possibilités de rendu de sensations tactiles par les ICI.

Contexte

Le Projet LobbyBot

Cette thèse a été développée dans le cadre du projet LobbyBot de l'Agence Nationale de la Recherche (ANR). Le projet LobbyBot consistait à développer une ICI qui sera intégré dans une application industrielle de prototypage de la cabine d'un automobile. Ce système a été designé à fin de recréer un cockpit automobile pour un prototypage plus rapide en VR pour le Groupe Renault, une entreprise automobiliste française. Dans ce processus de prototypage rapide, les concepteurs devaient explorer avec leur sens du toucher les différents matériaux, formes et objets pouvant être disposés dans un intérieur automobile facilement reconfigurable en RV. Ce nouveau paradigme a été conçu pour per-

mettre au Groupe Renault d'économiser le budget et le temps nécessaires à la fabrication de véritables cockpits automobiles, utilisés exclusivement à des fins de prototypage.

Applications

Les applications des ICI vont de l'industrie à la médecine, en passant par la recherche et le divertissement. Dans tous ces cas, les utilisateurs s'attendent à "rencontrer" une surface à toucher ou à manipuler dans un EV. Dans le cas des applications industrielles, ces dispositifs sont envisagés pour le prototypage virtuel nécessitant un retour haptique à différents positions afin de recréer des espaces de travail ou des objets à manipuler. Dans le cas du divertissement, les ICI sont utilisés pour recréer des éléments pouvant entrer en contact avec les utilisateurs lorsqu'ils interagissent dans un EV ludique. Dans le cas de la médecine, les ICI sont souvent utilisés pour de la palpation à distance et de l'entraînement sur des opérations chirurgicales. L'utilisation des ICI à des fins de recherche vise souvent à tirer parti des capacités des appareils à rendre des surfaces et des objets plus complexes. Certains de ces exemples sont illustrés dans la Figure A.1.

Domaines d'application des ICI

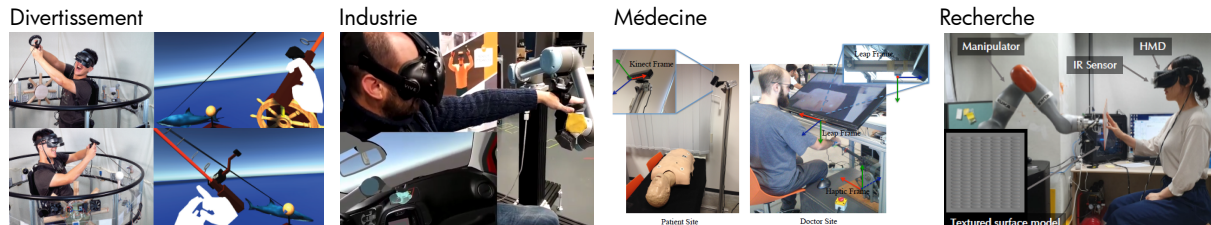


Figure A.1 – Domaines d'application des ICI. Ces développements ont été présents dans quatre domaines différents. Cette figure présente un exemple pour chaque domaine : (1) le divertissement, (2) l'industrie, (3) la médecine, et (4) la recherche.

Défis

Afin d'exploiter les capacités des ICI, plusieurs défis doivent être relevés dans différentes dimensions telles que l'utilisabilité, le retour haptique, et la performance des actionneurs. Ces défis sont divisés en questions de recherche (QR) que cette thèse aborde dans les chapitres suivants : (QR1) Sécurité de l'utilisateur ; (QR2) Techniques d'interaction pour l'exploration de surface ; (QR3) Rendu de grandes surfaces ; (QR4) Rendu de sur-

faces multiples ; (QR5) Manipulation d'objets ; (QR6) Optimisation des algorithmes de contrôle ; (QR7) Diversification des actionneurs. Ces questions sont présentées plus en détail ci-dessous.

Axes de recherche

Les deux principaux axes considérés pour les contributions de cette thèse sont l'utilisabilité et le retour haptique. Ces axes de recherche et les contributions qui en découlent sont illustrés dans la Figure A.2.

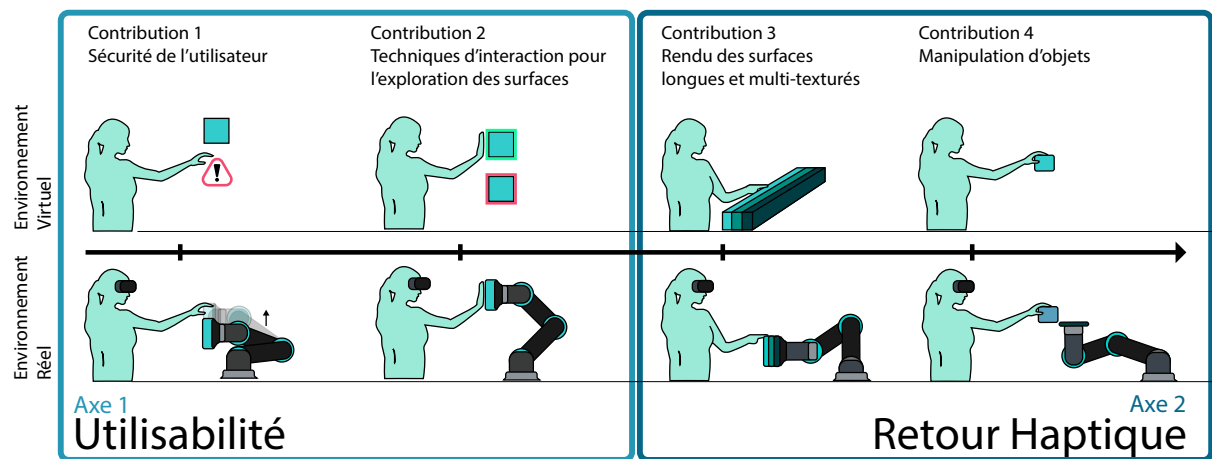


Figure A.2 – Le chemin de thèse. Cette figure montre comment les contributions sont organisées selon les axes de recherche et leur présentation dans les chapitres de la thèse.

Les deux premières contributions de cette thèse visent à améliorer l'utilisabilité des ICI. Le premier axe présente une première contribution (C1) consistant en un ensemble de techniques de sécurité basées sur le retour visuel pour équilibrer l'immersion des utilisateurs et la sécurité perçue. Une seconde contribution (C2) aborde l'exploration de grandes surfaces avec un ensemble de techniques d'interaction conçues pour optimiser le rendu des surfaces avec les ICI. Les deux contributions suivantes de cette thèse visent à améliorer le retour haptique des ICI. Le second axe portant sur le retour haptique présente une approche (C3) pour le rendu de grandes surfaces multi-textures avec les ICI. La deuxième contribution de cet axe propose une approche sur la manipulation d'objets avec les ICI (C4).

Les contributions de la thèse sont présentées dans les prochains chapitres.

Chapitre 1: Etat de l'art

Dans ce chapitre, nous avons examiné la littérature existante sur la recherche en matière des ICI. L'objectif de cette revue était de fournir une analyse des technologies existantes, de rendu haptique, des techniques d'interaction et des domaines d'application. Ce chapitre a présenté trois contributions principales : une définition du terme *Interface à Contact Intermittent (ICI)*, une taxonomie pour classer les différents types d'actionneurs ICI, et une analyse des travaux de recherche présents dans la littérature.

La définition des ICI que nous avons proposé a été basée sur les principales caractéristiques des travaux de la littérature. Cette définition pourrait servir de guide à la communauté des chercheurs en haptique pour distinguer correctement les ICI des autres types d'interfaces haptiques.

La taxonomie présentée dans ce chapitre tient compte des principaux types d'actionneurs robotiques examinés : à base fixe et mobiles. Le type d'actionneur à base fixe a été subdivisé en sous-types: bras robotique et de plate-forme fixe. Le type mobile a été subdivisé en sous-types: les drones, les plates-formes mobiles et les portables.

Ce chapitre présente également une analyse comparant le retour haptique, l'interaction, et les applications pour les différents types d'interfaces haptiques reportés dans la taxonomie susmentionnée. Le retour haptique comprend des procédures de contact et d'exploration haptique, notamment : le mouvement latéral, la pression, le contact statique, le maintien sans support, la saisie, le suivi de contour, le test de mouvement de pièce, et le test de fonction; [76]. Les interactions qui peuvent être réalisées à l'intérieur d'une EV à l'aide d'un ICI peuvent être classées comme suit : exploration de surface, manipulation d'objets, téléopération et locomotion. Ces procédés sont mis en applications principalement dans quatre domaines: : l'industrie, le divertissement, la médecine et la recherche.

Cette revue de la littérature a révélé plusieurs limitations auxquelles les chercheurs doivent faire face pour créer des ICI capables de rendre un retour haptique similaire à celui que les utilisateurs ressentent lorsqu'ils touchent des objets réels. Les différentes pistes de recherche mises en évidence dans cette taxonomie seront abordés dans les prochains chapitres.

Chapitre 2: Sécurité de l'utilisateur en utilisant des ICI

Pour commencer, nous présentons une contribution (C1) abordant les questions de recherche liées à la sécurité des utilisateurs (QR1) et à la conception des techniques d'interaction (QR2).

Assurer la sécurité de l'utilisateur lorsqu'il interagit avec une ICI dans un EV immersive représente un défi pour les concepteurs et les chercheurs, car deux facteurs clés doivent être contrebalancés pour assurer une interaction optimale avec le système. D'une part, l'immersion de l'utilisateur doit être favorisée pour ne pas perturber la tâche et le "réalisme" que l'ICI fournit lors du retour haptique. D'autre part, la sécurité perçue par l'utilisateur doit être assurée en fournissant des informations appropriées sur le comportement du système. Ce compromis entre immersion et sécurité perçue doit être pris en compte dans la conception de techniques de sécurité permettant d'éviter les collisions involontaires avec une ICI.

Nous avons proposé un ensemble de techniques de sécurité basées sur le retour visuel pour aider aux utilisateurs à éviter les collisions involontaires avec ces interfaces. Ces techniques ont été créées dans le cadre d'un *design space* qui prenait en compte les caractéristiques liées au retour visuel rappelant aux utilisateurs la présence d'une ICI. Un *design space* pour servir d'outil d'aide à la conception de techniques de sécurité pour les ICI basées sur le retour visuel.

Le *design space* a été organisé en blocs décrivant l'aspect et le moment du retour visuel afin de protéger l'utilisateur. 18 techniques ont été créées à partir de ce *design space* (voir Figure A.3). Ces techniques ont été regroupées en différents groupes : bloqueurs, signaux, barrères, rayons de trajectoire, et révélateurs. L'itération des différentes techniques visait à proposer des solutions qui équilibrent la sécurité perçue par les utilisateurs sans rompre leur immersion dans le système. Pour ce faire, un ensemble de critères a été proposé pour évaluer les techniques, et on été utilisés dans une dans une évaluation préliminaire par un ensemble d'experts afin d'évaluer l'efficacité des techniques pour maintenir l'immersion et la sécurité perçue des utilisateurs. Les critères primaires pris en compte étaient l'immersion et la sécurité perçue. Par la suite, un ensemble de critères secondaires a également été pris en compte, notamment : l'encombrement visuel, la colocalisation, l'adaptabilité écologique, la conscience du dispositif, la charge mentale et la confiance de l'utilisateur. Un groupe d'experts a été recruté pour évaluer les techniques proposées en

fonction des critères d'évaluation.

Les résultats suggèrent que certaines techniques du groupe des révéléurs (*Révélation complète* et *Révélation graduelle*) pourraient équilibrer correctement le compromis entre l'immersion et la sécurité perçue. Les techniques du groupe des signaux ont eu tendance à être évaluées comme plus immersives, tandis que les techniques du groupe des limites ont obtenu un classement élevé pour la sécurité perçue mais faible pour l'immersion.

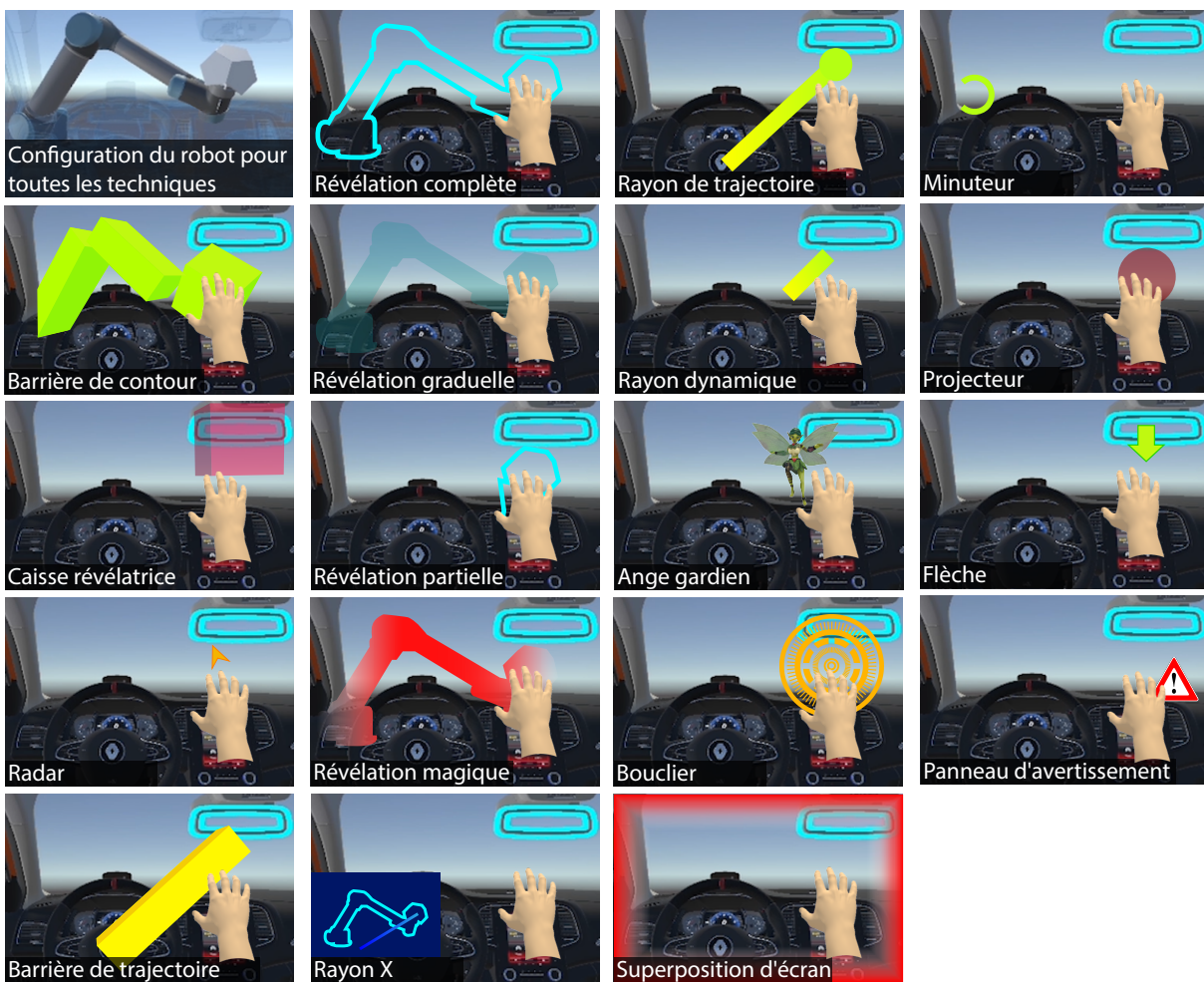


Figure A.3 – Illustration des 18 techniques de sécurité conçues. Les techniques de sécurité sont représentées dans un environnement virtuel représentant l'intérieur d'une automobile.

Chapitre 3: Conception de techniques d'interaction pour l'exploration des surfaces en utilisant des ICI

Nous avons proposé une contribution (C2) pour la **utilisabilité** des ICI en répondant aux questions de recherche liées à la conception des techniques d'interaction (QR2) et au rendu des grandes surfaces (QR3).

Cette contribution a été dédiée à étudier des techniques d'interaction pour les ICI pour l'exploration de surface. L'ensemble des techniques a été conçu dans un *design space* composé de quatre facteurs principaux qui font référence au contrôle des ICI : entrée, contrôle du mouvement, déplacement et contact. Les techniques ont été principalement conçues pour permettre à l'utilisateur d'interagir avec des surfaces virtuelles, plates et larges en utilisant un seul doigt. En utilisant ce *design space*, plusieurs combinaisons de caractéristiques ont été explorées pour concevoir 5 techniques : *Glissement*, *Embrayage*, *Déplacement*, *Bulle*, et *Suivi*.

Nous avons choisi d'illustrer nos techniques à travers un scénario d'utilisation avec une tâche de coloration de formes en utilisant une ICI. Cette tâche a été choisie car elle nécessite d'interagir avec une grande surface dans laquelle les informations de contact sont cruciales.

Une étude d'utilisateur a été menée pour évaluer les performances des techniques en termes de précision et de temps écoulé pour une tâche de coloration de formes. En outre, nous avons qualifié l'expérience utilisateur perçue par les utilisateurs comme un moyen d'identifier les fonctionnalités qui ont été mieux évaluées par les utilisateurs. Les résultats ont montré que les techniques *Embrayage* et *Déplacement* avaient de bonnes performances pour les critères de précision de peinture et d'expérience d'utilisateur. Les caractéristiques partagées par ces techniques sont le déplacement absolu, le déclenchement hors contact et le mouvement contrôlé par l'utilisateur. Les participants ont indiqué que le retour visuel affiché avec ces techniques les aidait à mieux comprendre le processus de rendu de surface. Dans l'ensemble, les contributions présentées dans ce chapitre pourraient aider à la conception de nouvelles techniques d'interaction adaptées à un plus large éventail de tâches, d'actionneurs et d'affichages de surface.

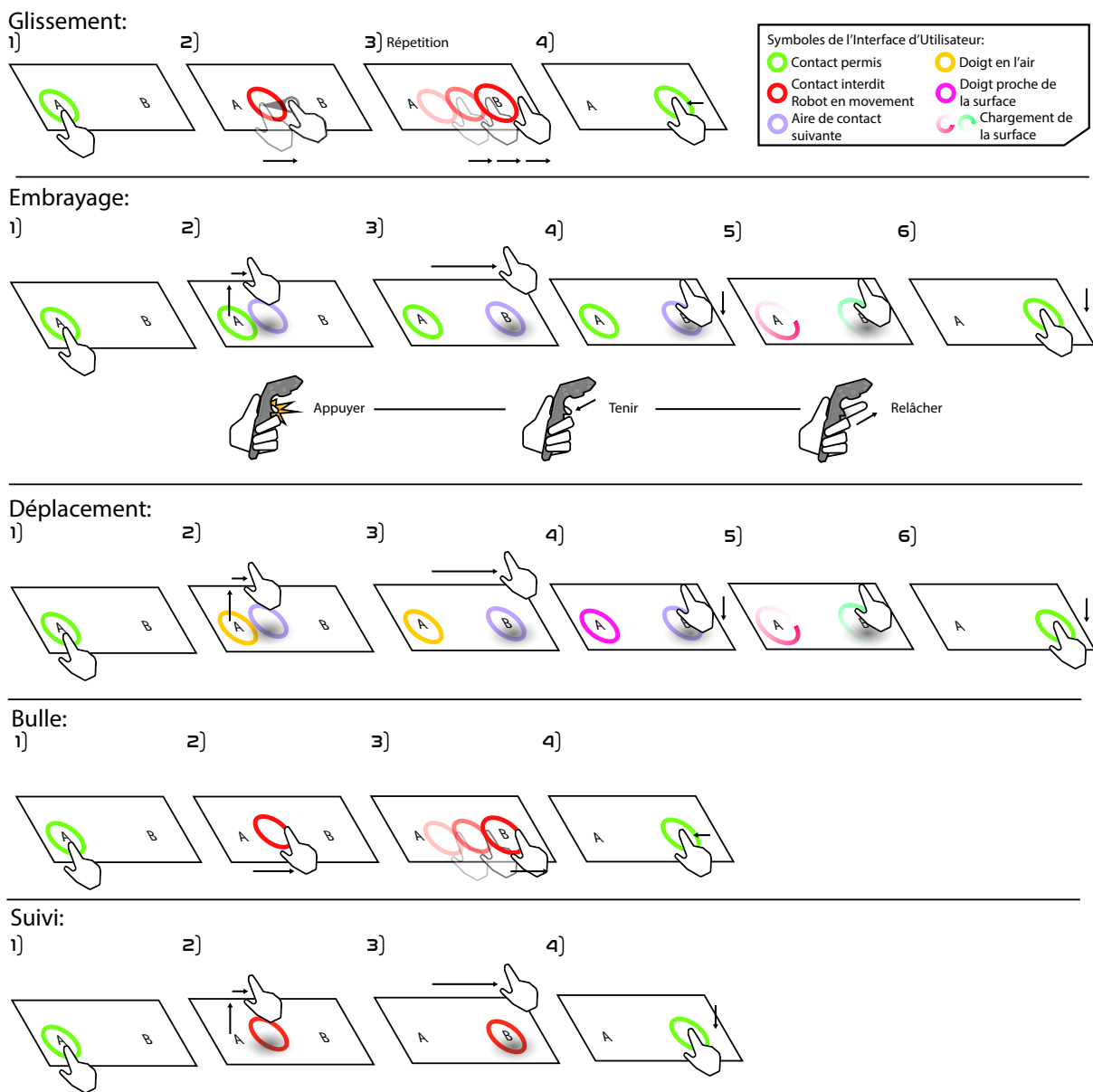


Figure A.4 – Techniques d'interaction. Cette figure illustre les différentes techniques d'interaction conçues en suivant les différentes branches de notre *design space*.

Chapitre 4: Rendu de grandes surfaces multi-texturisés en utilisant des ICI

Ensuite, nous avons présenté une contribution (C3) pour **retour haptique** des ICI en répondant aux questions de recherche liées au rendu de grandes surfaces (QR3) et au rendu de textures multiples (QR4).

Nous avons proposé une nouvelle approche appelée ENTROPiA (*ENcountered-Type ROtating Prop Approach*) pour faire le rendu haptique des surfaces virtuelles utilisant une ICI sans la contrainte d'une surface limitée en taille. Notre approche s'appuie sur une surface rotative comme moyen d'afficher une grande surface (voir Figure A.5). Cette approche repose sur le fait que les utilisateurs sont en contact avec une surface ronde tournante qu'un système robotique peut positionner et faire tourner en fonction de l'emplacement de la main de l'utilisateur. La sensation de toucher une surface plane est donnée par le mouvement de glissement de l'accessoire sous le doigt de l'utilisateur et l'intégration d'une technique d'interaction qui guide l'utilisateur dans l'exploration de la surface. L'interaction se déroule dans un EV à l'aide d'un casque de réalité virtuelle et d'un système de suivi. Les utilisateurs sont capables de toucher différentes surfaces texturées dans un EV en suivant une trajectoire qui leur permet d'explorer une grande surface avec leur sens du toucher.

ENTROPiA a introduit une nouvelle technique d'interaction destinée à optimiser la taille de l'affichage d'une surface multi-texturée ainsi que la zone de travail d'un système ICI. Une preuve de concept a été développée pour explorer plusieurs objets virtuels avec différentes textures, comme du bois, du cuir et du papier.

Une étude utilisateur a été menée pour évaluer la perception haptique des surfaces virtuelles simulées par notre approche. Dans cette étude, les participants ont été invités à explorer une grande surface selon différentes approches : toucher constamment une surface courbe statique, toucher constamment une surface plate statique, et l'approche ENTROPiA. Les réponses des participants étaient en faveur de notre approche comme moyen de rendre une sensation plus proche du toucher de la vérité du sol. ENTROPiA pourrait être utilisée pour optimiser le rendu de surface pour les ICI en profitant de la sensation donnée par la coordination de la rotation et de la position d'un accessoire cylindrique sous le doigt de l'utilisateur lors de l'exploration d'une grande surface dans une EV immersive.

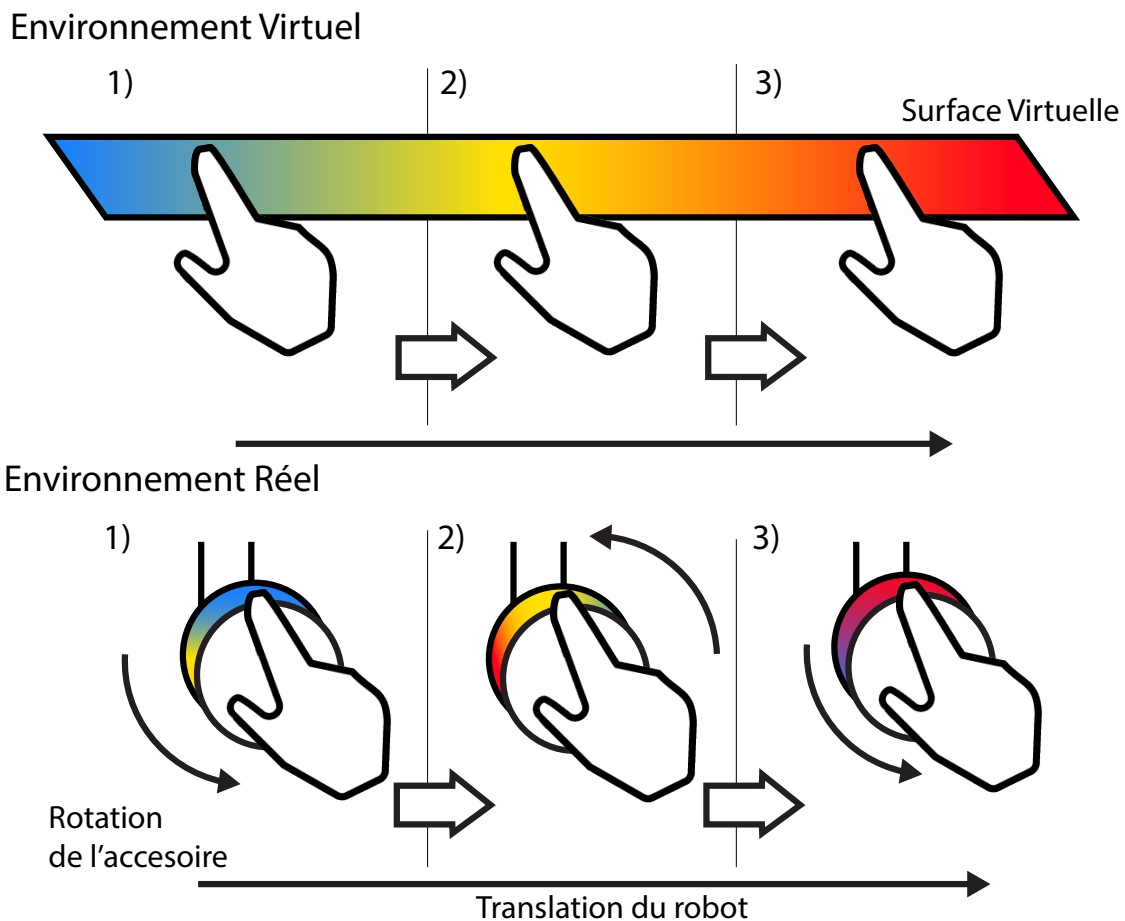


Figure A.5 – Le principe ENTROPiA. La sensation de toucher une surface plane dans un EV est donnée en touchant l'accessoire en rotation et en le déplaçant simultanément selon la même trajectoire et vitesse que le doigt de l'utilisateur. Les utilisateurs sont toujours en contact avec une "surface plane" qui se transforme continuellement au moment où ils déplacent leur doigt.

Chapitre 5: Manipulation d'objets en utilisant des ICI

Ce chapitre présente une contribution aux ICI (C4) **retour haptique** et **performance de l'actionneur** en abordant les questions de recherche liées à la manipulation d'objets (RQ5) et à l'optimisation de l'algorithme de contrôle (RQ6)

Finalement nous avons présenté "Alfred", une nouvelle approche pour la manipulation d'objets dans la RV en utilisant une ICI (voir Figure A.6). Alfred utilise un manipulateur robotique pour déplacer des objets tangibles dans son espace de travail de manière à ce qu'ils correspondent à la pose des objets virtuels avec lesquels il faut interagir. Les utilisateurs peuvent alors toucher, saisir et manipuler naturellement un objet virtuel tout en ressentant un retour haptique congruent et réaliste de la part du proxy tangible. Le proxy tangible peut se détacher du robot, permettant une manipulation naturelle et sans contrainte dans un EV.

Alfred a inclus une technique d'interaction qui permet aux utilisateurs de sélectionner, manipuler et relâcher des objets dans un EV. Cette technique d'interaction a été complétée par un algorithme qui optimisait le mouvement du dispositif lorsque les utilisateurs sélectionnaient ou relâchaient un objet dans la RV. En outre, ce chapitre présente trois scénarios illustratifs conçus pour montrer les principales caractéristiques d'Alfred : (1) un scénario de chaîne de montage industrielle qui permettait la réapparition et le retrait infinis d'objets virtuels, (2) un bar virtuel qui permettait le mappage de plusieurs objets virtuels à l'aide d'une seule procuration physique, et (3) un scénario d'empilement de bocaux qui permettait la reconfiguration libre de plusieurs éléments tangibles dans l'EV.

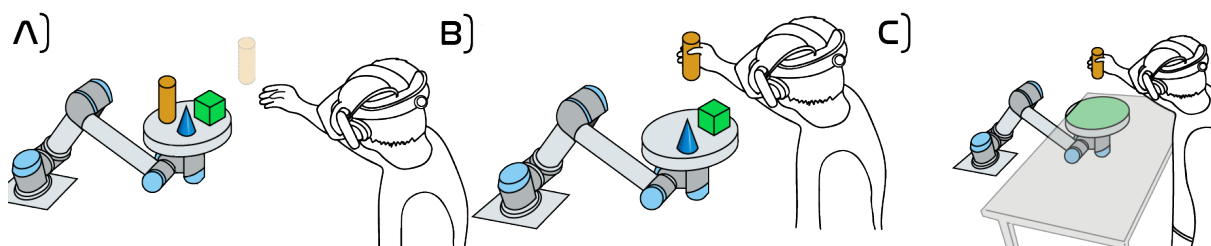


Figure A.6 – Illustration conceptuelle d'Alfred : (A) Un manipulateur robotique tient un ensemble d'objets tangibles capables de correspondre aux propriétés d'objets virtuels interactifs, en les plaçant comme il se doit pour qu'ils correspondent à la pose des objets virtuels avec lesquels les utilisateurs interagissent. (B) Lors de la saisie, un objet tangible se détache du plateau du robot et devient librement manipulable. (C) Pendant la manipulation, le plateau du robot agit comme une ICI, le plateau se positionne pour rendre des portions de l'EV, par exemple pour permettre à l'utilisateur de poser l'objet manipulé.

Alfred a été évalué selon quatre schémas de contrôle visant à optimiser le positionnement du dispositif lorsque les utilisateurs sélectionnent un objet à manipuler. Les résultats de cette évaluation suggèrent que le fait de suivre continuellement la main de l'utilisateur et de s'accrocher à la position cible pourrait permettre d'optimiser le rendu des objets de notre approche.

Conclusion

Cette thèse a présenté une série de contributions visant à améliorer les interfaces à contact intermittent, principalement sur les axes de recherche **utilisabilité** et **retour haptique**.

La première contribution sur l'axe de l'utilisabilité a étudié la conception de techniques de sécurité pour les ICI basés sur le retour visuel. Ensuite, une série de techniques d'interaction pour l'exploration de surface avec les ICI est présentée. Ces techniques ont exploré plusieurs combinaisons de facteurs liés au contrôle des ICI afin de donner aux utilisateurs la sensation de toucher une grande surface dans la RV.

Concernant l'axe du retour haptique, nous présentons une approche pour le rendu de grandes surfaces multi-texturées. Cette approche est basée sur un accessoire cylindrique rotatif, multi-texturé, attaché à l'effecteur d'un ICI. Finalement, la thèse présente une contribution à la manipulation d'objets dans la RV en utilisant un objet tangible détachable et un ICI. Cette contribution permet de créer, détruire et reconfigurer des objets tangibles dans des environnements virtuels immersifs.

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Titre : Contribution à l'étude de l'utilisabilité et le retour haptique des interfaces à contact intermittent.....

Mot clés : Interfaces à contact intermittent, Usabilité, Retour Haptique

Résumé : Les interfaces à contact intermittent (ICIs) sont des dispositifs robotisés qui suivent la main de l'utilisateur et se placent en position de rencontre lorsque l'utilisateur souhaite toucher des objets dans une réalité virtuelle (RV) immersive. Malgré ces avantages, plusieurs défis doivent encore être résolus en matière d'utilisabilité et de retour haptique.

Cette thèse présente une série de contributions pour tirer profit des ICIs à travers des axes de recherche focalisés sur l'utilisabilité et le retour haptique.

La première contribution dans l'axe de l'utilisabilité a étudié la conception de techniques de sécurité pour les ICIs basés sur le retour visuel. Ensuite, une série de techniques d'interaction pour l'exploration de surface avec les

ICIs est présentée. Ces techniques ont exploré plusieurs combinaisons de facteurs liés au contrôle des ICIs afin de donner aux utilisateurs la sensation de toucher une grande surface dans la RV.

Concernant l'axe du retour haptique, nous présentons une approche pour le rendu de grandes surfaces multi-texturées. Cette approche est basée sur un accessoire cylindrique rotatif, multi-texturé, attaché à l'effeteur d'un ICIs. Finalement, la thèse présente une contribution à la manipulation d'objets dans la RV en utilisant un objet tangible détachable et un ICIs. Cette contribution permet de créer, détruire et reconfigurer des objets tangibles dans des environnements virtuels immersifs.

Title: Contribution to the Study of Usability and Haptic Feedback of Encountered-Type Haptic Displays.....

Keywords: Encountered-Type Haptic Displays, Usability, Haptic Feedback

Abstract: Encountered-Type Haptic Displays (ETHDs) are robotic devices that follow the users' hand and locate themselves in an encountered position when users want to touch objects in immersive virtual reality (VR). Despite these advantages, several challenges are yet to be solved in matters of usability and haptic feedback.

This thesis presents a series of contributions to leverage ETHDs through research axes for both usability and haptic feedback.

The first contribution in the usability axis studied the design of safety techniques for

ETHDs based on visual feedback. Then, a series of interaction techniques for surface exploration with ETHDs is presented. These techniques explored several combinations of factors related to ETHD control to give users the sensation of touching a large surface in VR.

Concerning the haptic feedback axis, we introduce an approach for large, multi-textured surface rendering. This approach is based on a rotating, multi-textured, cylindrical prop attached to an ETHD's end-effector. Finally, the thesis presents a contribution to object manip-

ulation in VR using a detachable tangible object and an ETHD. This contribution permits creating, destroying and reconfiguring tangible objects in immersive virtual environments.