"Can I Touch This?": Survey of Virtual Reality Interactions via Haptic Solutions

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ABSTRACT

Haptic feedback has become crucial to enhance the user experiences in Virtual Reality (VR). This justifies the sudden burst of novel haptic solutions proposed these past years in the HCI community. This article is a survey of Virtual Reality interactions, relying on haptic devices. We propose two dimensions to describe and compare the current haptic solutions: their degree of physicality, as well as their degree of actuation. We depict a compromise between the user and the designer, highlighting how the range of required or proposed stimulation in VR is opposed to the haptic interfaces flexibility and their deployment in real-life use-cases. This paper (1) outlines the variety of haptic solutions and provides a novel perspective for analysing their associated interactions, (2) highlights the limits of the current evaluation criteria regarding these interactions, and finally (3) reflects the interaction, operation and conception potentials of "encountered-type of haptic devices".

CCS CONCEPTS

• **Human-centered computing → Virtual reality**; **Haptic devices**; **Interaction design theory, concepts and paradigms**.

KEYWORDS

haptics, Virtual Reality, human factors, haptic devices

RÉSUMÉ

Le retour haptique est devenu essentiel pour améliorer l'expérience utilisateur en Réalité Virtuelle (RV). C'est pourquoi nous observons une explosion du nombre de solutions haptiques proposées ces dernières années en IHM. Cet article est une revue de littérature des interactions en RV s'appuyant sur des dispositifs haptiques. Nous proposons deux dimensions pour décrire et comparer les solutions haptiques : leur degré de physicalité ainsi que leur degré de robotisation. Nous formulons un compromis utilisateur/concepteur, reflétant la variété des stimulations requises/proposées en RV, en opposition à la flexibilité des interfaces et leur déploiement en situation réelle. Ce travail (1) offre un panorama des solutions haptiques en RV ainsi qu'un cadre d'analyse pour étudier les interactions associées, (2) souligne les limites des critères d'évaluation actuels pour ce type d'interactions, et finalement (3) reflète les potentiels interactionnel, opérationnel et conceptuel des interfaces haptiques "à contacts intermittents".

MOTS-CLÉS

haptique, Réalité Virtuelle, facteurs humains, dispositif haptique

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1 INTRODUCTION

In the last few years, the terms "Virtual Reality" and "Haptics" have been amongst the most quoted keywords in HCI conferences such as ACM CHI or ACM UIST. Indeed, Head-Mounted Displays (HMDs) are now affordable and provide high quality visual and audio feedback, but augmenting the experience by enhancing VR through the sense of touch (haptic feedback) has become a main challenge. A large variety of haptic solutions has currently been proposed, nonetheless they have highly different scopes, due to the wide range of haptic features. It is hence difficult to compare their similarities and differences and have a clear understanding of the design possibilities.
In this paper, we present a survey of existing *haptic interactions* in VR. We use the terms "haptic interactions" to emphasize the focus on the users actions, and to analyse how the "haptic devices" influence their behaviours in VR.

We provide a synthesis of existing research on haptic interactions in VR and depict, from the required haptic features stimulation and interaction opportunities, a design space discussing and classifying the associated haptic solutions according to two dimensions: their *degree of physicality*, i.e. their physical consistency and level of resemblance as to replicating an object, and their *degree of actuation*, i.e. whether they rely on a motor-based hardware implementation enabling autonomous displacements of the interface (eg changing its shape or position) (Table 1).
This design space is useful to characterize, classify and compare haptic interactions and the corresponding haptic solutions. We also propose two criteria, User experience and Conception costs, highlighting the implicit trade-offs between the quality of the *user*

experience and the intricacy for the *designer* to implement these solutions. Both of the user's and designer's perspectives are hence considered in a novel framework to evaluate haptic interactions.
Finally, we illustrate the utility of our design space by analyzing and comparing four haptic solutions. This analysis indicates that (1) the use of real props in a virtual environment benefits the user experience, but limits the interactions to the existing props available within the VR arena; (2) the use of robotised interfaces enables more various interactions; (3) combining them offers the best user experience/design cost trade-off; (4) current evaluation methods do not allow a fair representation and comparison of haptic solutions.

We hence propose guidelines to evaluate haptic interactions from both the user and designer perspectives. We also outline how intertwining interfaces can expand haptic opportunities, by conducting a deeper investigation on Robotic Graphics interfaces [101] . Indeed, in the quest of the Ultimate Display [147], these show (a) the largest variety of interactions, (b) the most reliable interfaces through their automation, and (c) the most natural interactions as they encounter the users at their positions of interest without further notice.

2 BACKGROUND

Surveys in Virtual Reality consider the technology itself and its limits [188, 191], or more specifically its use-case scenarios. VR is indeed used in industries [20, 195], healthcare [103], or in gaming. In gaming, the concerns are mainly regarding the evaluation protocols [102], ie the presence [130] and its related questionnaires [131, 163]. Surveys for instance compare the results whenever the questionnaires are asked in VR or in the real world [9, 116]. The user behaviour in VR is also analysed, through gesture recognition [123] or system control techniques (eg menus) [25].
The research areas are coincidentally almost similar in haptics. Indeed, surveys analyse haptics themselves [164], haptic devices [63, 117, 132, 152] or examine the scenarios which benefit from a stimulation of the haptic cues. Haptics are used in telemanipulation [53], for training in the industry [22, 177] or for healthcare purposes [35, 118], or in gaming [78].

Finally, some surveys have been proposed at the intersection of VR and haptics and focus either on specific methods (pseudo-haptic feedback) [96], technology according to stimulated haptic features (temperature, shape, skin stretch, pressure) [42, 169] or the motivations and applications of each haptic device category [168]. In contrast our survey outlines the variety of haptic interactions and technologies in VR and provides a framework to analyse them.

3 SCOPE AND DEFINITIONS

The scope of this article is to analyse how a single user interacts and is provided with believable haptic feedback in Virtual Reality [97]. We thus define the terms "virtual reality" and "haptics" and how they are related.

3.1 Virtual Reality

Virtual reality corresponds to a 3D artificial numeric environment in which users are immersed in. The environment can be projected onto a large screen, in a simulation platform for instance, or multiple ones, such as with CAVE technology (where the image is projected onto at least 3 distinct walls of a room-scale arena). In this survey, we consider an artificial reality [172] where users do not perceive their physical vicinity: the outside world is not noticeable and users are fully immersed through a head-mounted display (HMD). For instance, augmented reality (AR), where the physical environment is augmented with virtual artefacts, is out of our scope.
Through a Head Mounted Display (HMD), Virtual reality creates immersive experiences for the users. These are only limited by the designers' imagination, and are evaluated through *presence*. Presence is defined as the "subjective experience of being in one place, even when one is physically situated in another" [139, 175]. It quantifies the users' involvement and naturalness of interactions through control, sensory, distraction and realism factors. This heavily relies on the sensory input and output channels, however, as VR was mainly integrating audio and visual cues, quantifying the haptic contribution in an experience remains difficult.

3.2 Haptics: Tactile vs Kinesthetic Perception

Haptics is the general term for the sense of touch. They are a combination of two cues: tactile and kinesthetic. The tactile cues are developed through the skin, while the kinesthetic ones come from proprioception and are through the muscles and the tendons.

3.2.1 Tactile cues: The skin is composed of four types of mechanoreceptors [87]. The first ones, "Merkel nerve endings", transmit mechanical pressure, position and shapes or edges. They are stimulated whilst reading Braille for instance. The second ones, "Ruffini corpuscle end-organ", are sensitive to skin stretch and provide both pressure and slippage information. The third ones are the "Pacinian corpuscles", which are sensitive to vibration and pressure. The last ones, "Meissner's corpuscles", are highly sensitive and provide light touch and vibrations information. It also contains thermoreceptors, which transmit information about temperature: the Ruffini endings respond to warmth, while the Krause ones detect cold. Through tactile cues, the human can hence feel shapes or edges, pressure, vibrations or temperature changes.

3.2.2 Kinesthetic cues: The kinesthetic cues rely on proprioception, ie the perception and the awareness of our own body parts positions and movements. Mechanoreceptors into the muscles, the "spindles", communicate to the nervous system information the forces muscle generate, as well as their length change [77]. The primary type of spindle is sensitive to the velocity and acceleration of a muscle contraction or limb movement, while the second type provides information about static muscle length or limb positions. Kinesthetic cues hence allow to feel forces, as well as perceiving weights or inertia.

3.3 VR & Haptics

Whenever we touch or manipulate an object, the combination of these two previous cues allows to understand its material, but also its shape and the constraints it implies to the user. On the one side, adding physical presence [92] through haptic feedback in VR enhances the users' immersion, even at an emotional and physiological scale: the heart rate of a user can literally increase with the use of haptics through real objects [73]. Haptics are also required for interacting with the environment: the user needs to control the changes in the environment [66] and to be aware of the modifications he physically has made (eg moving virtual objects, pushing a button). On the other side, haptics can benefit from VR. For instance, Lécuyer et al. leverage the users vision and analyse how it affects their haptic feedback [96]. This approach, "*pseudo-haptic feedback*", tricks the users' perception into feeling virtual objects' stiffness, texture, mass. Many more haptic features can be stimulated, such as temperature, shape, skin stretch, pressure.

4 ANALYZING HAPTIC INTERACTIONS

The main objective of this survey is to provide analytical tools to evaluate and compare haptic interactions.

4.1 Design space

We propose a two-dimension framework to discuss and classify haptic solutions in VR (see Table 1).

The first dimension is their *degree of physicality*, ie how the haptic perception is tangible/physically consistent/resembling with the virtual objects. This dimension is drawn as a continuum, from "no physicality" to "real objects" (see Figure 2). We find that this continuum can be discretised as a two-category section: whether they use real objects or not.

The second orthogonal dimension is their *degree of actuation*, ie whether haptic solutions rely on a motor-based hardware implementation enabling autonomous displacements (eg enabling to change its shape, position etc).

4.2 Analysis criteria

We consider two main criteria to analyse haptic interactions in VR. They cover both the user and designer perspectives.

The **User** experience is the first criterion and includes two aspects: interaction opportunities and visuo-haptic consistency/discrepancy. Interaction opportunities represent to which extent haptic solutions allow *users* to interact/act (e.g navigate, explore, manipulate) in a VR scene as opposed as in the real world. Visuo-haptic consistency/discrepancy refers to the tactile and kinesthetic perceptual rendering of these interactions. These two sub-criteria are complementary focusing on both action and perception.

The second criterion is the conception cost, i.e. the challenges **Designers** should address when designing haptic interactions. We distinguish implementation and operation costs. Implementation costs include several technical aspects related to the acceptability of a haptic solution such as safety, robustness and ease-of-use [42]. Operation costs include the financial and human costs required to deploy these technologies.

4.3 Application

We rely on this design space and criteria to highlight and understand the trade-offs between the user's interactions opportunities in VR, and the designers' challenges in conception. This survey offers a novel perspective for researchers to study haptic interactions in VR. It can be used to compare and analytically evaluate existing haptic interactions. For a given application, designers can evaluate the most adapted haptic interaction. For a given technique,

Physicality: Real Objects / Actuation: Robotics & Actuation	No	Yes
No	Shape Simulation Pseudo-Haptics Visuo-Haptic Illusions Object Primitives Surface Haptic Displays	Desktop Haptic Interfaces 2.5D Tabletops Shape-Changing Roboxels Controllers Wearables Electro-Muscle Stimulation Mid-Air Haptics Inflatable Room Floor
Yes	Passive Haptics Visuo-Haptic Illusions Pseudo-Haptics Human Actuators Real Props Reassignment	Robotic Shape Displays • Cartesian Robot • Robotic Arm • Swarm Robots • Mobile Platforms • Drones • Merry-Go-Round Platform

Table 1: We propose two dimensions to classify current technologies: their degrees of physicality and actuation.

they can evaluate a haptic solution depending on their needs (tasks, workspace, use-cases etc).

.We first discuss haptic interactions from the User perspective (Section 5 - Interaction opportunities, Section 6 - Visuo-Haptic Consistency/Discrepancy). We then adopt the designer perspective in Section 7. We use our design space on Sections 6 and 7, which emphasize haptic solutions.

5 INTERACTION OPPORTUNITIES

In the real world, users **move freely** without constraints, **pick any object of their environment** and then **interact with their bare-hands**. They also can **be interacted with**, from the environment (wind, unexpected obstacles) or from other users, for instance to catch their attention or to lead them somewhere. A natural environment also naturally physically constrains users through their **entire body**.

In this section, we discuss the interaction opportunities in VR and the methods available to provide them. In particular, we discuss them through four main tasks: navigation, exploration, manipulation and edition.

5.1 Navigation

We qualify a navigation task as the exploration of the environment through the vision and the ability to navigate through it via the users displacements. We identify three main techniques to navigate in VR. The two firsts rely on controllers and push buttons, where the users do not necessary physically move. The last one is more natural as it allows the users to walk in the VR arena.

5.1.1 Panning: With grounded desktop haptic solutions, such as the Virtuose [62], users need to push a button to clutch the devices and hence move within the environment.

5.1.2 Point & Teleport: With ungrounded solutions, such as controllers, the common technique is teleportation. Users point their controllers [14] to predetermined teleportation target areas, and are displaced in position but also in orientation [51] (Figure 1 - 1).

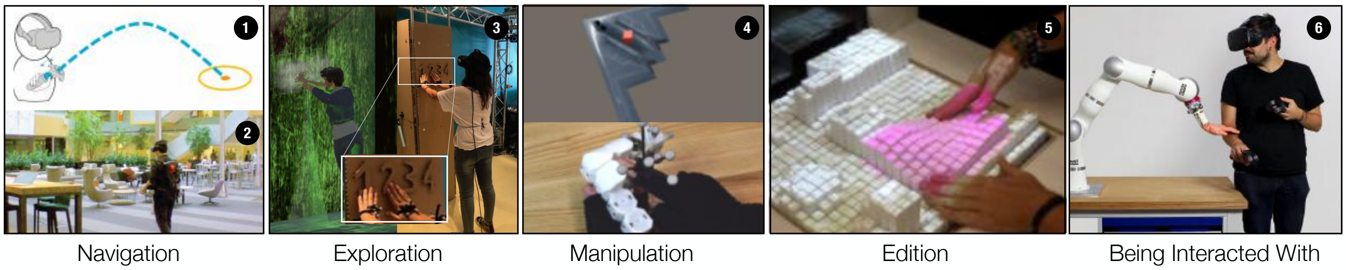

Figure 1: Tasks in VR: (1) Navigation through Point & Teleport [51]; (2) Navigation through a building, using redirection [27]; (3) Exploration with Bare-Hands: A user finds an invisible haptic code [24]; (4) Manipulation: Haptic proxies rearrange themselves to form a plane the user can manipulate [190]; (5) Edition: the user changes the shape of a haptic 2.5D tabletop [105]; (6) The user is interacted with by a robotic arm to feel emotions [155].

5.1.3 Real Walking: Real walking in VR, *"perambulation"*, has shown the best immersion and presence results [142, 162] because it relies on proprioception and kinesthetic feedback through the legs and gait awareness. Nonetheless, VR arenas are not infinite and HMD have a limited tracking space, hence methods need to be developed for the user to be able to move to any location of interest. One approach is to mount the previously discussed grounded desktop haptic solutions over mobile [49, 88, 89, 106, 111, 126] or wearable [17] interfaces. Users however still have to continuously maintain the handle in their palm. Other interfaces hence allow for free-hands Room-Scale VR [24, 170, 181]. For the users to perambulate in an infinite workspace, the virtual environment can also visually be warped for the users to unconsciously modify their trajectory or avoid obstacles [27, 119, 179] (Figure 1 - 2). This infinite redirection can also be provided from Electro-Muscle Stimulation (EMS) on the users' legs [12], with wearable electrodes. The user can also wear actuated stilts to perceive staircases [129] or a vibrating shoe to perceive virtual materials [145]. To remain unencumbered from these wearable techniques, the VR arena can also include robotised techniques: users can for instance walk on treadmills [50, 166], or on movable platforms that encounter their feet [74, 75].

5.2 Hand Interactions

In the real world, bare-hands interaction is important to execute everyday tasks (exploration, manipulation, edition). However, in VR, users commonly have to hold controllers, wearables or handles, which create a discrepancy between what the users feel and see [182]. These exploit the God-object principle [194], as opposed to bare-hands Real-touch interactions.

5.2.1 God-Object: The controller is considered as a continuity of the users' hands, represented by a proxy that does not undergo physics or rigid collisions, and is attached to a complementary rigid object with a spring-damper model. This latter hence moves along with the proxy, but is constrained by the environment. Whenever it does collide with an object of interest, the users perceive the previous spring-damper stiffness through kinesthetic feedback.
Users hence interact though a proxy, like a desktop mouse, which position is not co-located with the users' vision. Bare-hands interactions are not necessarily needed depending on the use-cases. For instance, in healthcare and surgery training, users are more likely to interact with a tool, such as a scalpel or a clamp. Continuously holding the god-object is hence not a constrain, however the co-location of vision and haptics is recommended [109].

5.2.2 Real Touch: In other scenarios, such as gaming, industry or tool training [143, 174], using the appropriate tools through props and real objects is more natural. The users however need to be able to reach them whenever required. Some interfaces (e.g. Robotic Graphics; see Section 7.3) are hence developed in these regards, to encounter the users whenever they feel like interacting.

5.3 Exploration

As opposed to the previous definition of "navigation", based on vision cues, an "exploration" task consists in the ability to touch the environment and understand its constraints. Exploring thoroughly an environment in VR can be done through different haptic features, and can improve the users depth perception [98] or distances to an object. The different methods for exploring the environment are detailed in Section 6.
Whenever a user is exploring the environment, shapes or textures are felt through his body displacements. He needs to move for his skin to stretch (through tactile cues) or his muscles to contract (through kinesthetic cues).

5.3.1 Through Tactile cues: Whenever real props or material patches are available, users can naturally interact with their fingertips to feel different materials [11, 41], textures [19, 93], temperatures [192] or to feel shapes and patterns through their bare-hands [24, 30] (Figure 1 - 3). When no physicality is available, a stimulation can still be performed. As seen in Surface haptic displays [18], vibrations between 80 to 400 Hz are felt through the skin, hence users perceive stickiness, smoothness, pleasure, vibration or friction, and for instance explore a 3D terrain or volumetric data [137]. Vibrations can then be combined with auditory and vision cues to render collisions in VR [23].

5.3.2 Through Kinesthetic cues: Exploring the environment can also be done through kinesthetic cues: the users can literally be physically constrained to feel a wall, using electro-muscle stimulation (EMS) for instance [95]. With the god-object principle, users can also explore the environments' constraints through force-feedback. In this configuration, the users' arms are constrained by haptic desktop interfaces, providing strong enough forces to simulate a physical collision and discriminate shapes.

5.4 Manipulation

A manipulation task is performed whenever modifying the position and orientation of an object.

5.4.1 Direct Manipulation: In VR, we distinguish the *direct manipulation* [26], *"the ability for a user to control objects in a virtual environment in a direct and natural way, much as objects are manipulated in the real world"* from pointing/selecting an object with controllers. A direct manipulation relies on the ability to hold an object with kinesthetic feedback, feel its weight [67, 95, 124, 134, 186, 187], shape [48, 85, 146], and constrains from the virtual environment, for instance when making objects interact with each other [24]. Changing a virtual object position or orientation can be used as an input in the virtual environment: in [190] for instance, the user modifies a light intensity by moving a handle prop in the real environment. By transposing [94] in VR, an object could even communicate its dynamic use to the user.

5.4.2 Pseudo-Haptic Manipulation: Leveraging vision over haptics allows to move an object with different friction, weights or force perceptions [115, 120, 121, 125]. For instance, visually reducing the speed of a virtual prop displacement leads to an increase in the users' forces to move it, modifying their friction/weight perceptions.

5.5 Edition

We qualify an Edition task as a modification of an object property, other than its orientation or position (for example through its scale [176] or shape).

5.5.1 Physical Edition: Editing an interface in VR requires it to be fully equipped with sensors. With wearables for instance, the hand phalanges positions are known, and can be tightly linked with an object property [165]. Knowing their own position, modular interfaces can be rearranged to provide stretching or bending tasks [46], or be pushed on with a tool to reduce in size [154].
Shape-changing interfaces have been developed to dynamically modify material properties [105] (Figure 1 - 5) or augment the interactions in Augmented Reality (AR) [91], however these techniques only consider HMDs and VR as future work directions.
These interfaces are relevant as 2.5D tabletops are already used in VR. Physically editing the virtual world through them could be implemented in a near future, by intertwining these interfaces with 3D modelling techniques [38].

5.5.2 Pseudo-Haptic Edition: The difficulty behind changing a real object property is to track it in real-time. This is why pseudo-techniques are relevant: they visually change the object properties such as their shape [7], compliance [90, 136], or their bending curvature [68] without physically editing the object.

5.6 Scenario-based Interactions

In the real world, humans are free to interact with any object without further notice. In this regard, common controllers enable interactions with any object through pointing, but they display a high visuo-haptic discrepancy. In more advanced haptically rendered Virtual environments, users are often constrained to scenario-based interactions: only a few interactable objects are available, accordingly with the scenario's progress.
The greater the virtual:physical haptic consistency, the harder it is to enhance non-deterministic scenarios, where the user is free to interact with any object with no regards to the scenario's progress. High quality haptic rendering in non-deterministic scenarios can be achieved through three methods: (a) numerous objects and primitives are available for interactions [69]; (b) the users' intentions are to be predicted prior to interaction to make it occur [24, 30]; (c) props modify their own topology to match the users expected haptic rendering [138].

5.7 Environment-Initiated Interactions

In both real and virtual environments with tangible interfaces, users usually are the decision makers and get to choose their points of contact during the next interaction. However, users themselves can be considered as tangible interfaces: uncontrolled interactions, such as being touched by a colleague, or feeling a temperature change in the environment [133, 192], are part of everyday interactions that can be transposed in Virtual Reality. Replicating a social touch interaction in VR for instance increases presence [71] or invokes emotions [155].
This type of interactions are recurrent in sports simulations, where the user is undergoing forces from his environment and perceiving impacts (jumping into space [58], shooting a soccer ball [167], goalkeeping in a soccer game [157], paragliding [180], intercepting a volleyball [60], flying [29]).
These interactions are involving multiple force types: tension, traction, reaction, resistance, impact that help enhancing the user experience in VR [170]. These can be strong enough to even lead the user through forces [24].

5.8 Whole-Body Involvement

All the previous subsections evoke interactions that mainly involve the hands or the fingers. This paradigm is revoked in [193]: a user should be able to choose his posture. This is currently only enabled in room-scale VR applications, where users experience sitting, standing, climbing or crouching [24, 36, 148, 154] and interact with their whole-body.

6 VISUO-HAPTIC CONSISTENCY/DISCREPANCY

Visuo-Haptic Consistency is the second aspect of the user experience. We exploit the dimension *degree of physicality* of our design space (Table 1) to discuss the different haptic solutions. In particular, we distinguish whether these solutions use real objects (exploiting real objects) or not (simulating objects).

6.1 Simulating Objects

Object properties that need to be simulated are their shape, texture, temperature, weight.

6.1.1 No Physicality, (Figure 2 - 1). Currently, grounded haptic devices such as the Virtuose [62] or the PHaNToM [100] simulate objects through their shapes (Figure 2 - 1). The rendering is only

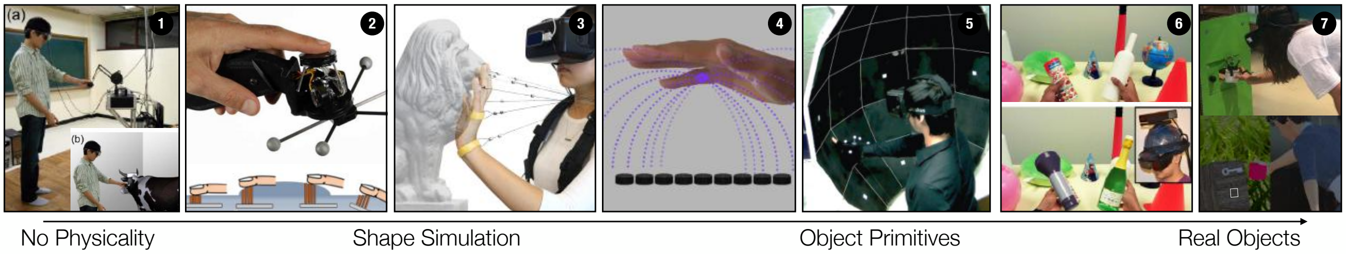

Figure 2: Degree of physicality continuum in VR.(1) Haptic desktop devices enable to explore the environment through a handle [89] with the god-object principle; (2) A controller [19] or (3) a wearable [45] simulate objects for exploration tasks; (4) Mid-air technology [117] create vibrations through the user's hand to simulate an object; (5) Passive proxies are oriented for the user to feel objects' primitives with their hands [30]; (6) Objects from the environment are assigned to virtual props with the same primitives [69]; (7) Real objects or passive props can be manipulated and interacted with each other [24].

done through kinesthetic feedback via a proxy. Conceptually, the ideal link between the users and this proxy is a massless, infinitely rigid stick, which would be an equivalent to moving the proxy directly [63, 127]. These solutions only provide stimulation at the hand-scale, with no regards to the rest of the body.

6.1.2 Shape Simulation, (Figure 2 - 2-3-4). In the same regard, gloves or controllers provide some physicality (Figure 2 - 2-3). Gloves or exoskeletons literally constrain the users hands for simulating shapes [2, 6, 8, 10, 32, 33, 45, 57, 104, 114, 158], or stimulate other haptic features such as stiffness, friction [165] or slippage [156]. These can be extended to overall body suits for users to feel impacts or even temperature changes [3, 37], or even intertwined with grounded devices to extend their use-cases [141].
Customised controllers are currently designed to be either stimulating the palm [39, 146, 185] (Figure 3 - 1, 2), or held in the palm while providing haptic feedback on the fingertips. For instance, [173] proposes interchangeable haptic wheels with different textures or shapes, while [19] enables textures and shapes and [90] displays compliance changes. In these configurations, users hold a single controller, however bi-manual interactions can be created by combining two controllers. Their link transmits kinesthetic feedback,

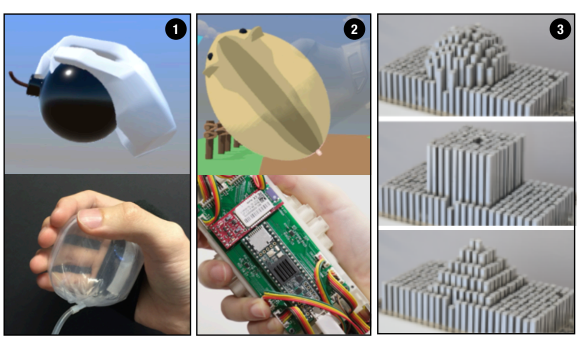

Figure 3: Simulating Objects. (1) A controller with an inflatable prop in the user's palm simulates holding a bomb [153]. (2) A pin-based interface shaped as a ball interacts in the user palm to replicate a hamster [185]. (3) Different primitives (ball, cube, pyramid) are displayed on a 2.5D tabletop [138].

and constrain their respective positions to each other [144, 171].
Contactless technology has also been developed for simulating shapes. While studies demonstrated that interacting with bare-hands increased the user's cognitive load [52], combining bare-hands interactions with haptic feedback actually enhances the users involvement. Since haptic feedback does require contact, "contactless" technology defines an interaction where the users are unencumbered, as per Krueger's postulate [172], and ultrasounds are sent to their hands, for them to perceive shapes on their skin, without a physical prop contact [117] (Figure 2 - 4).
These unencumbered methods are also achieved through shape-changing interfaces, for instance with balloons arrays [151] or 2.5D tabletops (Figure 3 - 3, Figure 1 - 5) [48, 76, 138]. These latter are constituted from pins, that raise and lower themselves to replicate different shapes. In the same regard, swarm interfaces rearrange themselves to display different shapes. These have mainly been developed in the real world [43, 79, 86, 99, 149, 150] but slowly take off as VR user interfaces [190] (Figure 1 - 4). Indeed, while these latter devices are used as desktop interfaces, the swarm robot idea has extended to the air, with drones for instance [54, 70, 81, 122, 160].
All of these previous interfaces embrace the **Roboxel** principle enunciated in *Robotic Graphics* [101]: "*cellular robots that dynamically configure themselves into the desired shape and size*".

6.1.3 Object Primitives, (Figure 2 - 5). Finally, a user can interact with object primitives. These represent the simplest geometries available: circle, cube, pyramid, cylinder, torus. Simply feeling an orientation through the fingertips provides the required information to understand an object shape, in an exploration task for instance. Panels with diverse orientations can hence be displayed for a user to explore various objects in a virtual environment [30] (Figure 2 - 5) or directly encounter the user at their position of interest [183, 184].
On the opposite, a bare-hands manipulation task requires multiple primitives to be available at the same time within the hand vicinity. This is why the exploitation of real objects is necessary.

6.2 Exploiting Real Objects

Passive haptics [73], ie the use of passive props, consist in placing real objects corresponding to their exact virtual match at their virtual position. Insko demonstrated that passive haptics enhanced the virtual environment [73]. Nonetheless, this does suffer from a main limitation: substituting the physical environment for a virtual one [135] requires a thorough mapping of objects shapes, sizes, textures, and requires numerous props [110]. This can be done with real objects in simulation rooms for instance (e.g plane cockpit, motorcycle), but cheaper methods need to be implemented to facilitate their use in other fields.

6.2.1 Object Primitives, (Figure 2 - 6). One solution is to extract the primitives of the objects that are already available in the physical environment, to map virtual objects of the approximate same primitive over them [69] (Figure 2 - 6).

6.2.2 Visuo-Proprioceptive Illusions & Pseudo Haptics. The number of props within the environment can also be reduced, while letting the users interact at different positions of the physical world. It is possible to leverage the vision over haptics and modify the users' proprioception to redirect their trajectory [13, 56, 61, 82–84]. A user might perceive multiple distinct cubes for instance, while interacting with a single one. On the same principle, the user hand displacement can be redirected at an angle, up-/down-scaled [4, 21], or slowed down for friction or weight perception [113, 125]. These techniques also allow for the exploration and manipulation of various shapes: models can for instance be added to enable complex virtual shapes to be mapped over real physical objects boundaries [189]. The user can also be redirected to pinch a multi-primitive object (cubic, pyramidal and cylindrical) from different locations, which theoretically widens the variety of available props with a single one [40]. On the same principle, pseudo-haptics allow to modify the users' shape [15, 16] or texture [41] perceptions when interacting with a physical prop.

6.2.3 Displacing Objects, (Figure 2 - 7). Whenever objects are indeed available within the environment, various directions are available to displace them. This displacement allows for mapping one physical object over multiple ones, but also to display a multitude of props. These directions embrace the *Robotic Shape Display* principle from *Robotic Graphics* [101]: "a robot that can reach any location of a virtual desktop with an end-effector" and matches the user's object of interest.
Their usability have been validated through a Wizard-of-Oz implementation, where human operators move real objects or even people around a Room-scale VR arena to encounter the users [31] (Figure 4 - 2). The users themselves can also reconfigure and actuate real props [28].
Robotic Shape Displays, RSDs, are also called **encountered-type of haptic devices**, as they literally encounter the users at their object of interest to provide haptic feedback. They allow to display real pieces of material [5, 11], physical props to simulate walls [24, 80, 178], or even display furniture [148] or untethered objects [24, 64, 65, 72], that can be interacted with each other.

7 CONCEPTION COST

In practice, designers have to trade-off their interaction design space with implementation and operational costs in the conception phase. Implementation costs include technical aspects related to the acceptability of an haptic solution such as safety, robustness and ease-of-use [42]. For instance, actuated haptic solutions require a special attention regarding this criterion. Operation costs include the financial and human cost for using a haptic solution. The financial cost is measured through the cost of the haptic device and additional elements such as motion capture systems to precisely track the users' hand or the prior preparation of required props. Human cost refers to both labour time and number of human operators required during the user's interactions. For instance, actuated haptic solutions generally do not require human operators (low human cost) but might be mechanically expensive.

In this section, we use our two-dimension design space (Table 1) to discuss haptic solutions according to their conception cost. As non-actuated solutions globally share the same approaches and have a low implementation cost, we discuss them together in the "No Robotics" subsection.

7.1 No Robotics

Regarding implementation costs, all non-actuated haptic solutions are safe, robust and easy-to-use. We depict here an important design choice when opting for these solutions: either the designer relies on **graphics solutions**, leveraging vision cues over haptic ones, or needs **operators** to displace or change the interactable props (see Table 1).

7.1.1 Passive Props. Passive props [73] only consist in placing real objects corresponding to their exact virtual match at their virtual position. They provide a natural way of interacting through the objects' natural affordances [107]. They however are limited to the available objects within the scene as they are not actuated. They only can be used in a scenario-based experience, where the target is known in advance. The environment hence requires a prop for each available virtual object.

7.1.2 Shape Simulation, Pseudo-Haptics, Visuo-Haptic Illusions, Object Primitives. For graphics solutions, users are redirected towards their object of interest [13] using visuo-haptic illusions. However, physically overlaying a prop or primitive over a virtual object has a tracking cost, which usually relies on trackers which can be operationally costly (eg Optitrack [108] or HTC Trackers).
Otherwise, the users intentions have to be predicted for the interaction to occur. The users hands are then redirected to the appropriate motionless prop, for them to explore their object of interest [30]. Operationally, the cost only relies on the proxy fabrication (Figure 2 - 5). These implementations offer various scenarios in terms of interaction (even non-deterministic), at an affordable cost.

7.1.3 Surface Haptic Displays. These techniques exclusively allow for exploration through multiple haptic features such as friction or textures. They also can integrate a tablet or a smartphone [128], on which the user can interact at any location.

7.1.4 Human Actuators. This technique consists in using human operators to displace props in the VR arena. The designers however come across reliability and speed issues with these operators. Even though they only are used in scenario-based experiences, *delay mechanisms* based on graphics need to be implemented [31] (Figure 4 - 2) to overcome these issues. Conceptually, they broaden the interaction scope, however this solution is operationally very costly.

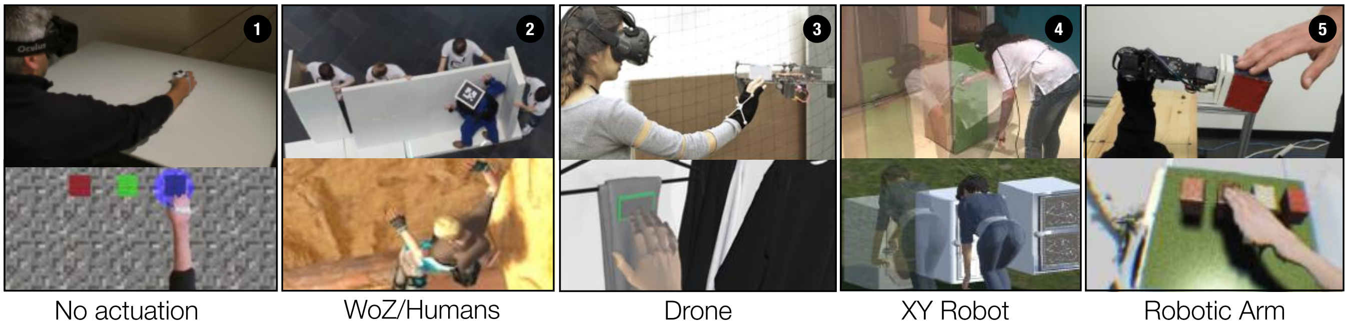

Figure 4: Degree of Actuation. (1) No actuation is available. The user's hand is redirected to touch a passive prop that cannot move [13]. The implementation of this technique relies exclusively on a software development leveraging the vision cues; (2) Human actuators are used to illustrate the Robotic Graphics [101] principle with a Wizard of Oz technique [31]. They carry props for the user to feel a real continuous wall; Encountered-type of haptic devices (3-5): (3) A drone encounters the users' hand for exploring passive props; (4) A cartesian robot displaces itself autonomously for users to interact with physical props [24]; (5) A robotic arm with multiple degrees of freedom displaces itself to encounter the users' hand, and rotates its shape-approximation device to provide the right material [11].

7.1.5 Real Props Reassignment. Instead of using a tracking system for passive props, a depth camera for instance allows to reassign props to different virtual objects of the same primitive [69] (Figure 2 - 6). The objects are hence all available to be interacted with. This drastically reduces the operational costs as they only rely on computer vision. This enables non-deterministic scenarios as the real world is literally substituted for a virtual one [135] and objects can be reassigned with virtual:physical [65] mappings.

7.2 Robotics & No Real Objects

This section gathers technologies simulating the virtual environment through actuation: they replicate it to constrain the users.

7.2.1 Desktop Haptic Interfaces. The SPIDAR [127], the Virtuose [62] and other classic desktop haptic interfaces are already compared in multiple surveys [42, 132, 168] (see Figure 2 - 1). They are safe as they are controlled by the user and only constrain their arm movements with kinesthetic feedback and adapt to any available object from the virtual scene (non-deterministic scenarios). They show a high perceived stiffness and robustness, but remain really expensive (>10k$).

7.2.2 Shape-Changing Interfaces, Roboxels, 2.5D Tabletops. These technologies present a high perceived stiffness and change their shapes accordingly with the virtual environment [47, 91]. They hence do not require any operator and allow for non-deterministic scenarios whenever their displacements are enabled [138] (see Figure 3 - 3). They are however complex to build and require multiple motors as they are composed of arrays of numerous pins, which define their haptic fidelity resolution. Even though they present high voltages, they remain safe around the users. As they require bare-hands interactions, they hence show a high ease of use.

7.2.3 Wearables, Controllers, EMS.. These rely on small torques, which are sufficient to constrain the users body parts. They are safe and easy to use, but in return are not robust enough to resist to users' actions. As they are continuously changing the users' haptic perception, they do allow non-deterministic scenarios and change their rendered stiffness and rigidity as a function of the distance to a virtual prop [39, 85]. A customised controller usually relies on 3D printed parts and small servomotors and can be easily replicated [146] (Figure 2 - 2,3; Figure 3 - 1,2).

7.2.4 Mid-Air Haptics. Providing contactless interactions, mid-air haptics also provide a high level of safety around the user. They however do not allow to navigate the VR environment, and hence cannot consider non-deterministic scenarios. Their robustness is very low, as they send ultrasounds to the users and do not physically constrain them [117].

7.2.5 Inflatable Floor. The floor topology can be modified and inflated to create interactions at the body-scale [154]. The users cannot inflate them, however they can push some tiles down and hence, *edit* them. These are safe, though they do not provide a wide range of interactions, but offer multiple static body postures.

7.3 Robotics & Real Objects

In this subsection, we detail the different types of Robotic Shapes Displays - otherwise known as "**encountered-type of haptic devices**", mentioned in the Table 1. First, these interfaces move to encounter the users: this feature optimises their ease of use. Second, as these interfaces move within the user vicinity, safety concerns are raised in this section, depending on the interfaces robustness. Encountered-type of haptic devices combine different types of interaction techniques: they can provide the users with passive props, textures or primitives, and allow navigation, exploration, manipulation tasks. Their mechanical implementations offer a good repeatability and reliability.

7.3.1 Cartesian Robot: In [24], CoVR, a physical column mounted over a Cartesian XY ceiling robot enables interactions at any height and any position of a room-scale VR arena (see Figure 1 - 2; Figure 4 - 4). This implementation presents a high perceived stiffness, and because it carries passive props around the arena, enables a high fidelity haptic rendering. It displays high accuracy and speed, and presents an algorithm which optimises the column's displacements as a function of the users intentions. It hence enables non-deterministic scenarios. Safety measures have been validated in the field. In practice, the column's celerity is decreasing around the user, as it is repulsed by this latter. Its software implementation ensures a safe environment for the user to perambulate in the arena without unexpected collision. However, in order to display many props in different scenarios, an operator is required to create panels and modify them. The materials however remain cheap, and even though its structure and motors are more expensive than 3D printed cases and servomotors, as per customised controllers for instance, this solution provides a wide range of interactions.

7.3.2 Robotic Arm: A robotic arm provides more degrees of freedom than the previous Cartesian robot. This primarily means a higher cost and a higher safety risk. For instance, H-Wall, using a Kuka LBR Iiwa robot, presents high motor torques and can hence increase the safety risks around the users. This implementation hence does not allow non-deterministic scenarios, and presents either a wall or a revolving door to the user, with a high robustness. Implementations with smaller torques, such as [11, 166] are safer but display a reduced perceived stiffness. The use-cases for all these interactions are hence drastically different: H-Wall simulates a rigid wall while VRRobot [166] and Snake Charmer [11] (Figure 4 - 5) present more interaction opportunities. This latter is also the single Robotic Shape Display that autonomously changes its end-effector, without an operator.

7.3.3 Drones, Swarm Robots, Mobile Platforms: With drones, the interactions are limited to the available props, for instance with a single wall at a given position [178]. Going from an active mode (flying) to a passive one (graspable by the user) has a long delay (10s) [5], which on top of the safety concerns, does not allow non-deterministic scenarios. [159] however allows the user to change the drone trajectory to fetch and magnetically recover an object of interest. Their accuracy and speed are limited [54, 122] compared to the previous grounded interfaces, and can require dynamic redirection techniques to improve their performances [5]. As they are ungrounded, they do not have a high robustness nor perceived stiffness. This is also valid for mobile robots, such as [55, 65], which only display passive props. To decrease the conception cost, existing vacuuming robots are used as mobile platforms in [170, 181]. Designers can choose to duplicate them, as swarm robots, to enable non-deterministic scenarios [148]. These are safe to use around the users, as their speed and robustness are limited. Instead of swarm mobile interfaces, a merry-go-round platform can also be designed to display various props at an equidistant position from the user [72]. All of the previous interfaces require an operator cost on top of their mechanical and software ones, to modify the interactable props available, depending on the use-cases.
On the opposite, [190] proposes autonomous reconfigurable interfaces intertwining both Robotic Shape Displays and Roboxels [101] principles to get rid of the operator cost (see Figure 1 - 4). These small robotic volume elements reconfigure themselves into the users objects of interest. They have a sufficient perceived stiffness to represent objects, but are not robust enough to resist to body-scaled forces, for instance to simulate a rigid wall.

8 EVALUATION PROTOCOLS

On top of choosing from the different trade-offs between conception and interaction opportunities, the designer also needs to pick-up an evaluation protocol. These protocols depend on the VR use-cases. For instance, the haptic benefits for medical or industrial assembly training can be evaluated against a real experience condition [112], with criteria such as completion time, number of errors, user cognitive load [59]. On the opposite, the haptic benefits for a gaming experience are more likely to be evaluated through immersion and presence, comparing "with/without haptics" conditions [31]. Although some papers do compare multiple haptic displays [44, 161], we point out the lack of referenced evaluation protocols for evaluating haptic solutions in VR.

8.1 Current Reference Evaluation Methods

The most common evaluation methods in VR are the SUS or WS presence questionnaires [140, 175]. These questionnaires mainly focus on graphics rendering and only two Likert-scale questions actually focus on haptic feedback: "How well could you actively survey the VE using touch?" and "How well could you manipulate objects in the VE?". Besides, most of the above technologies are evaluated against "no haptic feedback", hence the results can seem biased and most of all, *expected*. This justifies why some implementations provide results on single parts of the questionnaire, or arbitrarily combine their results [34] with new subsections (eg "ability to examine/act") or tasks specific questions (eg "How realistic was it to feel different textures?).

8.2 Evaluation Recommendations

Haptics should be more incorporated into the different factors enunciated in [175] ("Control, Sensory, Distraction, Realism"). In this direction, Kim et al. defined the *Haptic Experience model* [78], where they take into account both of the designer and user experiences. It depicts how Design parameters ("timeliness, intensity, density and timbre") impact Usability requirements ("utility, causality, consistency, saliency") and target Experiential dimensions ("harmony, expressivity, autotelics, immersion, realism") on the user's side.
In the same regards, we propose additional guidelines to evaluate haptic solutions in VR experiments (see Table 2). We believe that the different elements of interaction opportunities should be added to the *users control parameters*.

In the *sensory factors*, the **number of haptic features** available should be added (eg shape, texture, friction, temperature), in line with their quality, in terms of "timeliness, intensity, density and timbre". The **usability** requirements should **identify the use-cases and number of scenarios** with the proposed solutions. Hence, a good evaluation of the interface timeliness and usability should anticipate future deployments and avoid unnecessary developments.

9 EXAMPLES: ENCOUNTERED-TYPE OF HAPTIC DEVICES

We propose in this section to compare four encountered-type of haptic devices: Beyond the Force (BTF) drone [5] (Figure 4 - 3), ShapeShift [138] (Figure 3 - 3), Snake Charmer [11] (Figure 4 - 5), and CoVR [24] (Figure 4 - 4).

	Navigation Workspace	Haptic Features	Exploration	Manipulation	Edition	Whole-Body Involvement	Non-Deterministic Scenarios	Number of Props	Passive Haptics	Operator	Deployment Use-cases	Robustness	Accuracy Speed	Safety	Ease-of-Use	Evaluation Method
Beyond the Force	2 m^3	++	++	+	-	-	-	Prepared prior to use	Yes	Yes	/	-	-	-	+++	Noise & Fear Acceptance
ShapeShift	Desktop	+	+++	+	+	-	++	∞	No	No	3D Terrain VolumetricData	++	+	+++	+++	Shape Recognition
Snake Charmer	Desktop	+++	+++	++	-	-	++	Prepared prior to use	Yes	No	Training	+	+	++	+++	No Formal Evaluation
CoVR	30 m^3	+++	+++	+++	-	+++	+++	Prepared prior to use	Yes	Yes	Arcade Training	+++	++	+	+++	Users Enjoyment

Table 2: Comparison & Evaluation of 4 Encountered-type of Haptic Devices, according to the "Evaluation section" parameters.

In terms of interactions and number of props, the drone is the most limited one. Indeed, because of both safety and implementation limitations, it only enables free navigation in a reduced workspace. It also allows exploration (through textures) and manipulation tasks. However, the manipulation task is at the moment limited to a single light object as BTF cannot handle large embedded masses yet. Whenever grabbed, it does not provide a haptic transparency [63] during the interactions because of its thrust and inertia. For the users to perform different tasks, an operator needs to manually change the drone configuration. Its mechanical implementation does not provide a sufficient speed for overlaying virtual props in non-deterministic scenarios, but its accuracy is also unsatisfactory and requires dynamic redirection techniques for the interactions to occur. It also provides unwanted noise and wind, which reduces the interaction realism.

ShapeShift [138] is drastically different: it is a 2.5D desktop interface that displaces itself. Even though a drone is theoretically available in an infinite workspace, in practice they do share approximately the same one. As [138] relies on a shape-changing interface, no operator is required and it shape changes itself to overlay the users' virtual objects of interest, in non-deterministic scenarios. It allows a free navigation at a desktop scale, as well as bimanual manipulation and exploration. Both of these devices haptic transparency are limited as they are ungrounded solutions. We believe that ShapeShift could be updated to allow Edition tasks, by synchronising the users force actions with the actuated pins stiffness. In terms of haptic features, it simulates shapes and stimulates both tactile and kinesthetic cues. As per all 2.5D tabletops, it can be used in various applications: 3D terrain exploration, volumetric data etc. Its resolution seems promising as its studies shows successful object recognition and haptic search.

The same interactions are available at a desktop scale with Snake Charmer [11], which provides a wide range of props and stimulation, as each of its end-effector include 6 faces with various interaction opportunities (textures to explore, buttons to push, heater and fan to perceive temperature, handle and lightbulb to grasp and manipulate...). It also can change its shape approximation device, SAD (ie its end-effector), autonomously, using magnets. It follows the user hand and orient the expected interaction face of its *SAD* prior to the interactions: it hence enables non-deterministic scenarios. Besides, Snake Charmer has a promising future regarding its deployment: *LobbyBot* [1], is already in the Renault industry research lab, to enable VR haptic feedback in the automotive industry.

Finally, CoVR [24] enables the largest workspace as well as the highest range of interactions. The user is free to navigate in a 30 m^3 VR arena, and CoVR predicts and physically overlays his object of interest prior to interaction. These interactions include tactile exploration, manipulation of untethered objects (full haptic transparency), body postures. Indeed, CoVR is robust enough to resist body-scaled users, and shows over a 100N perceived stiffness and can carry over 80kg of embedded mass. CoVR can also initiate the interactions with the users, and is strong enough to lead the users through forces or even to transport them. Moreover, with the appropriate physical:virtual mapping [65], one physical prop can overlay multiple virtual ones of the same approximate primitive without redirection techniques. It however requires an operator to create, assemble and display panels on its sides.

Room-scale VR becomes more and more relevant, and Snake Charmer could benefit from being attached to an interface such as CoVR. Similarly, intertwining CoVR with a robotic arm autonomously changing its SAD like Snake Charmer or with a shape-changing interface could reduce its operational costs. This would display all of the Robotics Graphics concept capabilities.

10 CONCLUSION

We analysed in this paper haptic interactions in VR and their corresponding haptic solutions. We analyzed them from both the user and designer perspectives by considering interaction opportunities and visuo-haptic consistency, as well as implementation and operation costs. We proposed a novel framework to classify haptic displays, through a two-dimension design space: the interfaces' degree of physicality and degree of actuation.

We then evaluated these latter solutions from an interaction and conception perspectives. Implementation-wise, we evaluated the interfaces robustness, their ease of use as well as their safety considerations. From an operation perspective, we also evaluated the costs of the proposed solutions.

This survey highlights the variety of props, tasks and haptic features that a haptic solution can potentially provide in VR. This survey can be used to analytically evaluate the existing haptic interactions. It can also help VR designers to choose the desired haptic interaction and/or haptic solution depending on their needs (tasks, workspace, use-cases etc).

We believe that combining multiple haptic solutions benefits the user experience, as it optimises the above criteria. Encountered-type of haptic interfaces were then highlighted as they already combine multiple interaction techniques: they displace passive props in potentially large VR arenas and allow for numerous tasks, such as navigation, exploration, manipulation, and even allow the user to be interacted with.

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