Evaluating Touchless Haptics for Interaction with Virtual Objects

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Abstract. In recent years, touchless (mid-air, hands-free) haptic interactive concepts with machines have gained popularity due to their health benefits and accessible feedback in everyday items. In particular, touchless haptics are particularly effective in creating realistic virtual environments. This paper examines the performance and user experience of touchless haptics for manipulating virtual objects. A comparative study involving seven participants was conducted to evaluate the efficacy of a touch controller versus a touchless haptic system (Ultraleap). Participants tested three interaction techniques in a virtual environment, performing a range of control actions on various virtual objects, including adjusting the size and spatial position of geometric volumes and manipulating a lever. Results indicate that while the touch controller remains the preferred tool for simpler tasks due to its ease of learning, touchless haptics reveals nearly as effective when a virtual representation of the user's hands, as visual reference, is incorporated into the immersive environment. Under these conditions, both systems demonstrate comparable effectiveness for specific command and resizing tasks.

Keywords: Haptics · Interactive systems · Virtual Reality

1 Introduction

Nowadays, the growing commercial offer of head mounted displays (HMD) enables the consumption of virtual reality services and applications in different domains. Many of the existing HMD proposals are designed to be used as a computer peripheral (e.g. Oculus Rift, HTC Vibe, Play Station VR or PSVR, etc.), while others work standalone or leveraging the computing power and visualization of capabilities of smartphones. HMDs also differ on their capabilities. A relevant aspect is the vision angle (usually, the wider the better), as this factor influences on the immersive perception of the user. Typical values are 100°–110°; in some cases, the system includes an eye tracker, so it is possible to better focus on specific zones of the image, while others are faded, simulating the focus work performed by the human eye (to achieve a continuous immersive feeling without dizziness, the refresh rate must be above 60 frames per second (fps), being usual values above 90 fps).

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For navigation within the environment, it is usual that virtual reality systems include tracking and navigation features to manage the view in a realistic way. The most basic technique is to track the HMD position with 3 degrees of freedom (3DoF), taking as input the accelerometer, magnetometer and gyroscope inertial sensors. Advanced systems (such as PSVR) rely on 9 LEDs and an external camera to monitor position signals, while others rely on a wireless controller with sensors that are different to those in the smartphone (past Google Daydream, Samsung Gear VR or Google Cardboard). Some other techniques include joysticks, keyboards, voice commands or gloves. In this context, the fields of Virtual Reality (VR) and haptic interaction are obviously strongly related. VR offers to the user the possibility of getting into a realistic virtual environment; thus the user expects to interact in the same way as in the real world (i.e. physically).

In this article, we analyze to which extent touchless haptic interaction, enabled by an ultrasound device (Ultrahaptics Touch Development Kit UHK), may work equivalently to the one provided by a joystick-like controller interface. The UHK device tracks the hand position by using depth sensors and provides haptic feedback as an opposition force, which may implement different feeling patterns. For our tests, the objective would be to be able to provide feedback on the shape of a virtual object (a lever, a cylinder, a sphere, etc.), so the user can feel its boundaries and physically interact over it (to resize it, activate it, etc.).

The paper is structured as follows. Section 2 compiles related work. Section 3 details the implemented system, while Sect. 4 goes over the user study. Discussion and conclusions are presented in Sect. 5.

2 Related Work

The integration of haptic/physical interaction into the VR experience has been widely explored in literature, to enhance the feeling of intensiveness and achieve more realistic experiences and safer user interactions [1, 2]. The haptic component can be delivered by using wearable devices [3–7], such as fingertip tactile devices, soft robotic gloves, Novint Falcon haptic device [8], etc. User studies demonstrate that haptic feedback can improve the user experience, although devices are still bulky, and application targeted.

Contactless/touchless haptic technologies bring the benefit of not requiring instrumenting the user. Different approaches have been considered: fans or pressurized air jets [9, 10], subwoofers in an enclosed space to compress air through a narrow aperture (AIREAL [11] and [12, 13]), lasers [14–17], electric arcs (e.g. Sparklee [18]), and electromagnetic fields [19, 20] in some cases with the help of magnetic gel or wax resulting in perceptible sensations from the hair follicles [21]. But all these solutions have limitations in range or spatial and temporal resolution greater than ultrasound haptics, being this one an outstanding solution within this field.

The main advantages that make this technology stand out are its spatial resolution that allows the simulation of multiple points, a high degree of temporal resolution, thanks to its high sampling frequency and the speed of sound itself, which also allows almost instantaneous and continuous presentation [22].

Thanks to all this, it is recently receiving a great deal of academic and commercial interest, becoming more accessible thanks to commercials such as Ultraleap [23] and open source initiatives such us Ultraino [24] that have allowed its extension into new areas in works such as [25] where it is used an ultrasound phased array to provide haptic feedback in the mouth area, the second most mechano-receptive area after fingertips. Or the Contactless Elevator [26] which allows the creation of an elevator interface for visually impaired people allowing them to read Braille with an accuracy of 88%.

Combining haptic feedback with other types of feedback such as thermal feedback is also experimented with the work [27] by combining the ultrasound haptic display with a hot air source, or auditory feedback with [28] by having the ultrasound device itself generate sounds in addition to haptic sensations.

Although research is growing, it is not known exactly what the most attractive scenario for these technologies is, but for now where they are being used the most are in sterile medical interfaces such as UltraSendo [29] (the first application in the context of medical training simulators) or UltraPulse [30] (which allows trainee doctors to search for a pulse mimicking the pulsation effect), and also most recently [31] that used an AR and haptic feedback teleoperation ultrasound system, automotive applications that typically use ultrasound haptics to deliver feedback for interface control such as [32, 33]; digital advertising adding to visual and auditory modalities the tactile sensations to achieve more informative or entertaining experiences with the marketed products such as [34–36]; VR/AR where ultrasound haptics are unobtrusive maintaining freedom of movement and can represent a wide range of sensations like recreating physical objects using haptics such as HaptoClone [37] or [38]; other more recent applications to create novel entertaining experiences such as [39, 40] and Ultraleap with its "supernatural" feelings [41, 42].

Another line of research for VR interaction explores smart watches. Authors in [43] introduce a combination of smartphone (iPhone 6+ mounted on a Leap HD VR viewer) and smartwatch (Apple Watch Gen. 1) for fully immersive environments. To measure the effectiveness of the system, a second setup was built, consisting in the same VR system and a 3D camera for gesture recognition (Axus Xtion Pro Live). The user study shows that the interaction with the smartwatch obtains similar or better rating or better than the camera.

However, despite the progress in these technologies, ultrasound haptics is still in its infancy and needs more research to achieve both more effective systems and better understanding of perception in order to be able to recreate these sensations. In this work, we analyze to which extent mid-air haptic interaction, enabled by an ultrasound-based device (i.e. UHK), may work equivalently to the one provided by a standard haptic interface (i.e. graspable controller) to manipulate virtual objects.

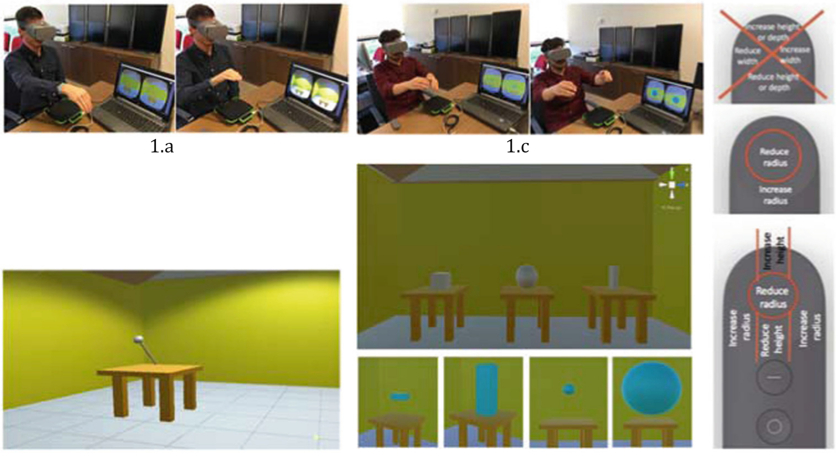
3 Components and Architecture

Our interactive system is built on two hardware solutions. The first one is a hardware kit composed by a headset and a controller; the latest is equipped with two buttons (APP and HOME), a touchpad and two lateral buttons for volume. The headset is ready to host a smartphone with high-quality graphics and resolution screen.

The second device is UHK, which is a 16 × 16 ultrasound transductors board that enables to provide contactless haptic feedback to the hands (touchless opposition force).

In practice, this means that a grid of small ultrasound speakers can be configured, in terms of number and height of control points, frequency and emission intensity to generate different feelings. The UHK device integrates the Leap Motion controller to locate the hand and detect gestures. Android, Unity and Unreal SDKs are provided together with the device. In this project, Unity has been our choice.

Additionally, a computer is used to plug UHK controller and to run the software associated to both devices and the interaction manager, which bundles the logic coordinating and sending the interaction commands to the mobile device. The computer is wirelessly connected to the smartphone, which oversees receiving the interaction commands and managing the virtual reality scenario. The graphical interface has been developed using Unity, together with some in-house developments to show the user movement when using the graspable controller.



1.a 1.c

1.b 1.d 1.e

Fig. 1. a) User interacting in the LeverScene; b) Lever scenario; c) User interacting in the ResizingScene; d) Resize object scenario, overall view and prism and sphere manipulation. In the second case, it is also necessary to physically select the target object; e) Controller configuration. (Color figure online)

On this system, two prototypes have been built. The first one, LeverScene, enables to handle a lever in a virtual environment, to control the lighting level of a room. The lever is controlled by pushing or pulling a virtual lever object. The haptic system simulates the lever object by providing column-shaped feedback that varies depending on the user's hand movement. To manipulate it, the user must place her hand on the top of the fictional column, in the same way she would do it with a real object (Fig. 1a). The second one, ResizingScene enables the user to modify the size of different virtual objects (i.e. a prism, a sphere and a cylinder) using both hands. The system provides simulate air volumes consistent with shapes (shaped air columns with specific boundaries and power) that are to be constrained or expanded depending on the hands position (Fig. 1c).

With respect to the interaction handled through the controller, the coordinates transformation applied over the touchpad enables the user to move to all directions depending on the active part of the touchpad. Additionally, by touching the upper part of the touchpad, the user will always move forwards the direction to which she is looking at. To manipulate the lever with the controller, the user will have to scroll fingers on the touchpad. To manipulate an object, the user will have to navigate the environment to approach to it until it gets activated (the object will be highlighted in blue). Then, to start interaction with the object, the user will have to press the standard APP button. After that, the touchpad's sections have been organized to enable every type of resizing for the proposed objects.

4 User Study

4.1 Method

The main hypothesis to verify in the user study is that "H0: Both mid-air haptics (UHK) and graspable touch provide equivalent efficiency and satisfaction to the users when manipulating virtual objects".

Seven participants (volunteers among the research personnel), with ages between 22 and 44 and no previous experience on the use of the technologies in the study, completed the test. Independent variables were the control technology (3 options) and the interactive scenarios (2 options). Regarding control technologies, participants were asked to use: 1) Graspable controller, 2) UHK without visual feedback and 3) UHK with hand-pose visual feedback. The first test scenario required the user to handle a virtual lever to control the lighting in a virtual room (3 tasks). In the second scenario, it was possible to resize some virtual 3D volumes in their different dimensions: cube (4 tasks), sphere (3 tasks) and prism (4 tasks). A total of 27 tasks per participant were evaluated (Table 1), 9 with each technology. The order of the six [technology, scenario] pairs were randomized for each participant, finally getting 189 valid tasks. For the sake of time, users were requested to complete only two manipulation tasks for each object; the type of tasks to complete for each object were also randomized for each user at the beginning of the test (the pairs [object, task] were completed for the 3 control technologies).

Prior to the use of each technology, the participant had a training time, that was concluded when the user explicitly stated to feel ready to start with the test (5 min was the limit). After each technology trial, a SUS (Standard Usability Scale) questionnaire and some extra questions specifically designed were completed; some open additional questions regarding preferences and opinion were posed to conclude the test.

In these conditions, the following *dependent variables* were defined:

- *System performance*, measured by success rate and number and error types, execution time to complete each task and learning time.
- *Usability*, calculated from adapted questions in the System Usability Scale Questionnaire.
- *Preference ranking*, the order of technology preference for the user.

Errors were classified into three groups: a) *Timeout*: The user is not able to finish the task in less than the average completion time (calculated over all participants) plus one standard deviation. b) *Task failure*: The user finishes the task, but the result does not lie on the success criteria. c) *System error*: The system is unexpectedly blocked or shut down (the system needs to be restarted).

Table 1. Tasks to perform in each scenario, with the success metrics.

Objects	Task list	Success criteria
Lever	Pull the lever up to the maximum lighting level	$\alpha < -40^{\underline{\circ}}$
	Bring the lever back to initial position, no light	$\alpha > 40^{\underline{\circ}}$
	Pull the lever up to the vertical position	$-5^{\underline{\circ}} < \alpha < 5^{\underline{\circ}}$
Prism	Min prism size in its 3 dimensions	Min size: $w, d, h < 0.3$ Max size: $w, d > 1$; $h > 1.4$
	Min size in 2 dim. & max in 1 dim.	
	Min size in 1 dim. & max in 2 dim.	
	Max size in 3 dim	
Sphere	Min size	$r < 0.5$
	Max size	$r > 1.9$
	Medium size	$0.8 < r < 1.2$
Cylinder	Min radius and height	$r < 0.2, h < 0.25$
	Min radius and max height	$r < 0.2, h > 0.8$
	Max radius and min height	$r > 0.8, h < 0.25$
	Max radius and height	$r > 0.8, h > 0.8$

4.2 Results

On System Performance. Regarding *success rate*, no technology was able to offer full reliability to complete the proposed tasks for all the participants (Table 2). As expected, the controller was the most efficient solution; around an additional 20% of tasks were completed when using the controller, taking the UHK success rate as a reference. Around 12% of errors were *time out* ones, while the rest were due to not fulfilling the success criteria.

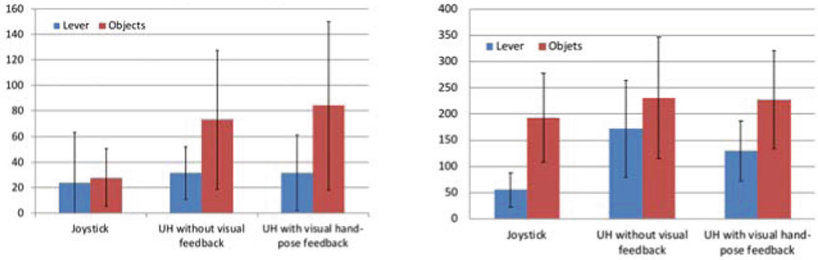
Table 2. Success rate for each scenario-technology combination. The second column indicates, for the tasks that were more difficult to complete (min) and easier (max) how many users were able to successfully finish them.

Scenario-technology	Success rate	Min—Max no of users
Lever-controller	86%	[4..7]
Lever-UHK without visual feedback	67%	[2..6]
Lever-UHK with hand-pose feedback	62%	[3..6]
Objects-controller	88%	[6..7]
Objects-UHK without visual feedback	69%	[3..7]
Objects-UHK with hand-pose feedback	67%	[3..6]

When analyzing the *execution time* (Fig. 2a) by the participants to complete the tasks, a Wilcoxon signed-rank test for paired samples shows that in the Lever Scenario, the median difference between joystick and UHK without visual feedback times is not statistically significant ($p_{lever} = p_l = 0.12$), while it is for the joystick and UHK with hand-pose feedback times ($p_l = 0.05$). In the objects scenario, it is possible to reject the null median time difference hypothesis for both pairs of technologies ($p_{objects} = p_o << 0.05$). Regarding the influence of visual feedback when using UHK, no statistical significance is found independently of the scenario ($p_l = 0.476$, $p_o = 0.759$).

Taking execution time into consideration, a set of Kruskal-Wallis tests show that it is not possible to state that the seven participants are differently skilled in the use of the systems neither as a whole ($\chi^2(6) = 11.76$, $p = 0.067$) nor when taking into consideration the three-available interaction means separately (controller: $\chi^2(6) = 5.9$, $p = 0.43$; UHK without visual feedback: $\chi^2(6) = 6.9$, $p = 0.33$; UHK with visual feedback: $\chi^2(6) = 7.84$, $p = 0.25$).

Regarding *learning time* (Fig. 2b), a Wilcoxon signed-rank test for paired samples shows that the median difference is not statistically significant in the Lever Scenario when comparing controller and UHK without visual feedback ($p_l = 0.063$, $\alpha = 0.05$), while it is in the controller and UHK with hand-pose feedback ($p_l = 0.018$). In the Objects Scenario, the difference is not significant neither for the controller-UHK without visual feedback pair ($p_o = 0.31$) nor for the controller-UHK with hand-pose feedback ($p_o = 0.091$). With respect to the comparison between UHK with or without visual feedback, the same test shows that it is not possible to reject the null hypothesis of zero median difference ($p_l = 0.31$, $p_o = 0.735$) for both scenarios.



2.a 2.b

Fig. 2. a) Average task execution time (in seconds), for the 3 technology combinations, compared for the 2 testing scenarios. b) Average learning time (in seconds) comparison, for the 2 testing scenarios. Error bars show 1 standard deviation.

On Usability. After finishing each [scenario, technology] test, in order to evaluate *usability*, participants were asked to complete a System Usability Scale questionnaire (SUS), a simple, ten-item scale giving a global view of subjective assessments of usability [14]. Results (Table 3) show that, on average, the controller solution achieves the highest SUS value of 78/100, while the UHK option gets 64/100 when hand-pose feedback is provided and 50/100 when there is no visual feedback. The three technologies were ranked as less usable in the Object Resizing scenario.

Table 3. System Usability Scale rating, with standard deviation and p-value for paired samples Wilcoxon signed-rank test with significance value 0.05.

Scenario-technology	$SUS/100$	*std*	$p(\alpha = 0.05)$
1. Lever-controller	83	21.2	$p1 - 2 = 0.063$
2. Lever-UHK without visual feedback	54	23.8	$p1 - 3 = 0.351$
3. Lever-UHK with hand-pose feedback	77	13.7	$\mathbf{p2 - 3 = 0.028}$
4. Objects-controller	74	17.7	$\mathbf{p4 - 5 = 0.027}$
5. Objects-UHK without visual feedback	45	23.3	$\mathbf{p4 - 6 = 0.046}$
6. Objects-UHK with hand-pose feedback	52	26.2	$p5 - 6 = 0.051$

In the case of the Lever Scenario, a set of Wilcoxon signed-rank tests show that the difference in the obtained SUS rating comes to be statistically significant only in the case of comparison of UHK-based solutions, when comparing the solution with visual hand feedback against the one with no feedback. In the Objects Resizing Scenario, the null hypothesis of zero median between technology pairs can be rejected for both pairs of controller-haptic solutions.

Interaction conditions the quality of the perceived immersive experience: the controller solution (over 10, mean $\eta = 7.86$; standard deviation $\sigma = 1.68$) and the UHK with hand-pose visual feedback ($\eta = 7.86$; $\sigma = 1.86$) are the ones providing the best immersive experience in the Lever Scenario. In the Objects Resizing one, the controller solution is the best rated ($\eta = 7.57$; $\sigma = 1.61$), followed by the UHK with hand-pose visual feedback ($\eta = 6.29$; $\sigma = 2.14$).

Some questions regarding the easiness of performing resizing over different dimensions of the geometrical figures show that resizing the prism depth is the task showing worst control ($\eta = 4.5$) while controlling its width ($\eta = 6.5$) is easier. The action of modifying radius obtains reasonable evaluations both for sphere ($\eta = 7.5$) and cylinder ($\eta = 7$). Regarding height, it is also efficiently done, both for prism ($\eta = 7.3$) and cylinder ($\eta = 7.3$). Coherently with the previous analysis on technology solutions, the controller is the proposal providing the best control ($\eta = 7.9$; $\sigma = 1.8$), followed by the hands improved UHK ($\eta = 6.5$; $\sigma = 2.4$) and the UHK with no visual feedback ($\eta = 5.5$; $\sigma = 2.8$). For both UHK solutions, the actions to modify prism depth ($\eta_{\text{no\_hands}} = 2.5$; $\eta_{\text{hands}} = 4$) and width ($\eta_{\text{no\_hands}} = 4.7$; $\eta_{\text{hands}} = 6.6$) are the worst rated.

On Preferences

Regarding preference, five out of seven participants state that the preferred system is the joystick ($\eta = 6$ in a 1–7 Likert scale of perceived control), followed by the UHK ($\eta = 4.7$ over 7) with hand-pose feedback. When asked about the possibility of building a multimodal interaction system, eye tracking was pointed by five participants, while voice was pointed by three of them. A participant talked about the possibility of building a system using a sensor-equipped bracelet.

With respect to open comments, some interested notes were gathered. While four participants did not mention fatigue, two pointed out that the use of UHK was more tiring than the joystick control, and another one told exactly the opposite. Regarding the

UHK solution, one participant stated he was feeling lost without hands representation, and another one pointed out the (obvious) difficulty of finding the correct position on top of Ultraleap controller when wearing the HMD. A participant complained on the unstable behavior of the systems, while three of them pointed out that they had enjoyed the experience.

5 Discussion and Conclusions

In this paper, we have presented a user study which aims at comparing the performance and usability of a touch graspable interface (controller) vs. a mid-air haptic one (UHK with and without hands representation) to perform tasks within an immersive virtual environment. With the controller, spatial touch movements enable us to manage the dimensions or movements of objects, while the UHK is programmed to generate simulated air volumes (through air flow columns), so the user can manipulate the objects by 'touching' them, through directional hand movements. Even if the user sample is small, the work gives some hints on to which extent both interaction methods may be effective and acceptable for the proposed scenarios (lever and objects).

The first issue to consider is that only two participants (over seven) were able to complete all the proposed tasks by using the controller, even after a learning session. This fact shows that the commercial technology for immersive interaction might still have a learning curve that may be steepest than desired. Participants that obtain higher hits with the controller also do it with the UHK alternatives, although no causality has been proven.

Neither the controller nor the UHK-based system has revealed as a perfect interaction tool for the proposed immersive environments. Both devices (controller and UHK) require that the user gets familiar to them. Actually, the learning time has demonstrated to be equivalent independently of the interaction technology in use. For example, the resizing tasks are more difficult to manage with the controller than the pull-push lever actions (as the touch space has to be divided into smaller sections). The user takes a similar time to learn how to perform the interaction either with the controller or the UHK.

Regarding execution times and tasks hits, the controller is obviously more efficient than the UHK-based proposal. Participants state that it is easier to use the touch controller, although mid-air haptic interaction with hands representation provides a better immersive experience.

No significant difference in terms of execution time has been found between the two UHK options (with/without hands), although the presence of the virtual hands as a reference is highly appreciated by the users. A non-expected effect is that, with the UHK, all the participants have managed to better complete the proposed tasks when they were not able to see their hands in the virtual environment. The learning time was also more reduced in the case of the Lever Scenario. There is not a real improvement in time execution or success rate related to the presence of hands references. This might be since the hands' view may complicate the interactive response, as users are less flexible to accept misalignments that are not relevant to complete the action.

In any case, users have positively assessed the mid-air haptic experience, although most participants prefer this method for simpler tasks (i.e. to control the lever, in this testing space) and specific applications. It is important to note that the mid-air touch system still offers limited capabilities, e.g. technical difficulties related to hands detection in specific hand postures (e.g. when the palm is perpendicular to the surface) makes more challenging some resizing tasks, finger tracking is only correctly done by UHK at a specific height from the device that may not be natural for the user, etc. Thus, depending on the interaction requirements, we feel that replicating the physical interaction model may not be the best option to guarantee the best success rate in terms of task completion. The creation of a proposal of a new vocabulary involving haptic feedback may be something to consider integrating this type of interaction with mid-air tools.

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