ORIGINAL RESEARCH

Haptic Zoom: An interaction model for desktop haptic devices with limited workspace

Alexis Gutiérrez-Fernández[a], Camino Fernández-Llamas[a], Gonzalo Esteban[a] and Miguel Á. Conde[a]

[a]Robotics Group, University of León, León, 24071, Spain

ARTICLE HISTORY
Compiled February 7, 2024

ABSTRACT
Haptic devices can be used to feel through the sense of touch what the user is watching in a virtual scene. Force feedback devices provide kinesthetic information enabling the user to touch virtual objects. However, the most reasonably priced devices of this type are the desktop ones, which have a limited workspace that does not allow a natural and convenient interaction with virtual scenes due to the difference in size between them and the workspace. In this paper, a brand-new interaction model addressing this problem is proposed. It is called Haptic Zoom and it is based on performing visual and haptic amplifications of regions of interest. These amplifications allow the user to decide whether s/he wants more freedom in movements or an accurate interaction with a specific element inside the scene. An evaluation has been carried out comparing this technique and two well-known desktop haptic device techniques. Preliminary results showed that haptic zoom can be more useful than other techniques at accuracy tasks.

KEYWORDS
Interaction techniques; force feedback; human-computer interaction

1. Introduction

Haptic refers to a form of tactual perception in which both the cutaneous sense and kinesthesis convey significant information about distal objects and events (Loomis & Lederman, 1986). Moreover, haptic devices allow users to feel objects, textures and weights simulated in a computer-generated virtual scene through the sense of touch. The relationship between the sense of touch and haptic devices can be compared to that of the sense of sight and screens. While screens allow the visualization of the elements of a virtual scene through the sense of sight, haptics allow the user to feel and interact with said elements through the sense of touch (Srinivasan & Basdogan, 1997).

Haptic technology is often classified based on how the end-user receives feedback information; hence the terms *tactile* and *force feedback* devices. The first type provides cutaneous sensations (perceived through the skin), whereas the second stimulates the proprioception (i.e., the sense of body location and forces), providing the kinesthetic senses of force and motion (Schneider, MacLean, Swindells, & Booth, 2017). On the

CONTACT Alexis Gutiérrez-Fernández. Email: alexis.gutierrez@unileon.es

one hand, tactile devices allow feeling an object's properties such as volume, roughness, temperature, etc. and can be further classified as *vibrotactile* or *electrotactile* interfaces (Chouvardas, Miliou, & Hatalis, 2008). Furthermore, force feedback devices enable the user to feel an object's properties such as weight and inertia as well as shape and texture (Riener & Harders, 2012). That being said, the most popular haptic devices currently in use are force feedback and vibrotactile (Giri, Maddahi, & Zareinia, 2021). However, for those tasks in which the user interaction requires fine manipulation of objects within an environment, (e.g., drawing or writing on a piece of paper), the use of force feedback interfaces is actually more widespread due to their fidelity in recreating certain aspects of proprioception present during the development of such tasks (Richard, Pietrzak, Argelaguet, Lécuyer, & Casiez, 2021).

Likewise, haptic technology can also be classified according to the exploration methods provided to to end-user by the hardware in order to perform haptic interactions. Therefore, it is possible to discriminate between active and passive interfaces (Rodríguez et al., 2019). For the former, the end-user explores the environment by both controlling and feeling motions through the end-effector; while for the latter, the device itself controls the motions and the end-user simply feels them during the same process. But, considering the two taxonomies mentioned above, both tactile and force feedback devices can be classified as *active* devices. However, the active–passive taxonomy also considers the inflow of haptic data to represent the information displayed by the devices to the end-users; thus, distinguishing between *input* and *output* information. Consequently, force feedback can be considered to be both input and output interfaces (as they can sense and exert motion), but tactile devices are only considered output interfaces (they simply apply motion).

Before proceeding, it must be noted that the paper will focus only on force feedback devices, as tactile devices have been discarded, based on the limitations explained above.

Force feedback devices are commonly referred to as haptic devices and can be further classified as wearables and desktop ones (Burdea, 2000). Wearable haptic devices, such as GhostGlove (Minamizawa, Kamuro, Fukamachi, Kawakami, & Tachi, 2008) or Dexmo Glove (Gu et al., 2016), allow natural interaction through gestures and haptic feedback, as well as having a large workspace which is only limited by the system to which the device must be connected and by the user's movements. However, the greater the wearability of a haptic device is, the greater the loss of the kinaesthetic component of the interaction (Pacchierotti et al., 2017). Besides, the availability in the market of wearables haptic devices is restricted and only few are commercially available, at a high price (e.g., around 50,000 USD for Dexmo Glove). Moreover, their output force is compromised by the size of the actuators (0.5 N in Dexmo Glove). On the other hand, desktop haptic devices are limited by their physical nature: their internal components are anchored to a base, causing them to have a narrow workspace. Despite this, they are very popular thanks to their value for money. For example, the PHANToM^{TM} (Massie, Salisbury, et al., 1994) stands out thanks to its availability in the market, its affordable price and the maximum force it can exert (around 2,800 USD and 3.3 N for PHANToM^{TM} respectively).

In this context, force feedback desktop haptic devices can be either designed and built for a specific field of application—with particularities of said field (*HelpMeSee Eye Surgery Simulator*, n.d.; *Simodont Dental Simulator*, n.d.)— or have a general purpose—applicable to several fields (*Force dimension omega haptics*, n.d.; Massie et al., 1994)—. The latter, also referred to as commercial haptic devices, have the advantages of a general design aiming to fit in as many situations as possible and at a reduced cost in comparison to those devices specifically built for one task.

Another point to highlight is that force feedback desktop haptic devices find their main limitation in their small workspace (Burdea, 2000). The main drawback of this kind of device when interacting within a virtual scene is that their movement is constrained by their physical workspace, which is not always suited to the needs of the virtual workspace of the scene itself (this being generally larger). This is the reason why models or techniques applicable to this kind of haptic device are needed, so that they may be used as the main interaction devices in computer-generated virtual scenes. These techniques should tackle the problem of controlling virtual scenes bigger than their workspace while using the device, thereby maintaining an acceptable level of precision in the tasks that are being developed.

Regarding this issue, a new interaction technique is proposed in this paper. Our approach is based on the concept of "haptic zoom", which complements the classic "visual zoom" in order to provide both freedom of movement and different levels of precision when interacting haptically within a virtual scene. However, it must be noted that in the literature the term "haptic zoom" is often used in reference to another concept. Therefore, and in order to clarify the contribution of our paper, it is necessary to define what is currently defined as "haptic zoom" in such a context. To this end, a systematic literature review following the guidelines of Kitchenham et al. (Kitchenham, Budgen, & Brereton, 2015) has been carried out. The results have revealed five studies describing techniques that focus on the limited workspace in desktop haptic devices.

In a preliminary search, the words "haptic zoom" have been used in order to identify those studies that could potentially overlap with this one. In the works of Ziat et al. (Ziat, Gapenne, Stewart, Lenay, & Bausse, 2007) and Rastogi & Pawluk (Rastogi & Pawluk, 2013), the term haptic zoom is applied in techniques for tactile haptic devices rather than force feedback ones. The study of Magnuson & Rassmus-Gröhn (Magnuson & Rassmus-Gröhn, 2003) uses a force feedback haptic device for allowing visually impaired people to explore virtual traffic environments. The zoom is mentioned but it is barely described, and it seems to consists of increasing the size of the objects rather than of actually zooming on the scene.

The technique presented by Pavlik et al. (Pavlik, Vance, & Luecke, 2013) is based on mounting the desktop haptic interface on a mobile robotic base. In order to compute the position of the virtual avatar, not only the end-effector position inside the device workspace is taken into account, but also the location of the base. In this way, a bigger workspace is achievable, but it is also limited by the space in which the base can move. Besides, as the base only moves in a single plane, this technique causes a discrepancy between the dimensions of the plane itself (those in which the robotic base is applied) and the remaining one.

Li et al. (Li, Akkil, & Raisamo, 2019) presented a new interaction technique in which gaze tracking is performed in order to control the position of the virtual avatar. Thus, users can feel in their hands the objects they are looking at. However, this solution requires extra hardware to work, and it offers less ease of use in terms of kinesthetic perception.

Liu et al. (Liu, Liu, Zhang, & Wang, 2014) presented a robot teleoperation technique for desktop haptic devices. It consists of: 1) using the haptic interface as a joystick for positioning the robot arm in the area of interest; and 2) changing the operation mode in order to allow a natural operation. The switching between modes is carried out by pressing a key in the keyboard so it cannot be applied in those scenarios in which the user cannot type on a keyboard (for example in virtual reality experiences).

In the solution proposed by Conti & Khatib (Conti & Khatib, 2005) the end-effector is slightly moved towards the center of the workspace and there is no visual representation of that movement while the avatar is in motion. The technique takes advantage of the fact that humans are very influenced by what they see and do not notice the deviations. However, this technique does not generalize well and it is not effective if the user wants to interact with an object far away in the workspace, as the drift is not large enough to reach it.

Lastly, the bubble technique presented by Dominjon et al. (Dominjon, Lecuyer, Burkhardt, Andrade-Barroso, & Richir, 2005) consists of the division of the workspace into two subspaces: a bubble in the center and an external area that occupies the rest of the space. In the scene, this takes the form of a semi-transparent bubble which contains the virtual avatar. While the end-effector moves within the limits of the bubble, a high level of precision is achieved because there is no scaling factor. When reaching another point of the scene is required, the bubble can be moved by placing the end-effector outside the bubble, which is centered in the workspace. However, it must be noted that an artificial elastic radial force is applied to the haptic's end-effector when the bubble is in movement. Consequently, such forces can alter the real haptic perception of an object if the avatar touches it during its repositioning.

In view of the above, this paper presents a new interaction model, applicable to force feedback desktop haptic devices, which tackles and solves the problems previously described for these devices, but in a natural and efficient way for the final user.

2. Materials and methods

2.1. Haptic control paradigms

The techniques designed to use force feedback desktop haptic devices as the main devices in human-machine interaction can be classified into three groups depending on their way of functioning (Dominjon et al., 2005; Hou & Srinivasan, 1998): techniques based on position control, those based on rate control, and hybrid techniques.

2.1.1. Position Control

Position control-based techniques use the position of the device physical location where force feedback is transmitted, that is, the end-effector of the device—inside the physical workspace—to consequently calculate the position of the virtual avatar.

This techniques can be found in interaction models used traditionally by haptic devices such as clutching (Dominjon, Perret, & Lécuyer, 2007) and direct or scaled mapping (Fischer & Vance, 2003; Hirzinger, Brunner, Dietrich, & Heindl, 1993). Clutching is a technique adapted to haptics from its previous use in desk mice. It consists of lifting up the mouse and placing it down again in a more comfortable position when a single movement is not enough to reach the area of interest. Applied to haptics, this technique consists of decoupling the movement of the end-effector from that of the virtual avatar while, for example, a button is pressed. By repeating this action, it is possible to reach any part of the virtual scene, even if the haptic's workspace is limited. Meanwhile, direct and scaled mapping establishes a correspondence between the workspace of the device and the size of the virtual scene with which it is interacting. Usually, this is achieved by defining a scaling factor, which entails, in large-scale scenes, a small movement of the end-effector of the device causes a big movement in the virtual avatar.

An example of more advanced techniques can be found in the aforementioned ones by Conti & Khatib's (Conti & Khatib, 2005) and Pavlik et al. (Pavlik et al., 2013) .

2.1.2. Rate / Force Control

Rate control-based techniques base their functioning on the deviation between the end-effector of the device and the center of its workspace. While the end-effector stays in the center of the workspace, the virtual avatar does not move. However, once the end-effector is outside of the center of the workspace, the avatar moves in the direction of the end-effector, increasing in speed the farther away the end-effector is from the center (Hou & Srinivasan, 1998). It can be considered then, that when a rate control technique is implemented in a haptic device, it starts to function like a joystick.

However, pure rate control-based techniques are not usually applied in haptics because of their lack of naturalness when receiving force feedback. No articles were found that present new haptic interaction techniques based on this paradigm.

2.1.3. Hybrid Techniques

Lastly, hybrid techniques combine both position control and rate control techniques in a single technique, establishing a mechanism that decides when each technique should be used.

This was first introduced by Hollis and Salcudean (Hollis & Salcudean, 1993) and it is implemented in the aforementioned bubble technique, proposed by Dominjon et al. (Dominjon et al., 2005), as well as in teleoperation technique from Liu et al. (Liu et al., 2014).

2.1.4. Comparison of Techniques

In an evaluation carried out by Hou and Srinivasan (Hou & Srinivasan, 1998), both position control and rate/force control techniques were compared. The experiment was based on a maze that users had to overcome as quickly as possible using techniques from both groups. Necessary time, wall contact errors and wall crossing errors performance measures were recorded as well as subjective comments for each one of the groups. Results showed that the time needed for overcoming the maze was on average 50% lower when using a position control technique and error rate was also better with this type of technique (0 vs. 44 on average). Besides, a higher level of satisfaction was reported by users when using a position control based technique, finding this kind of technique easier to use than rate/force control techniques.

2.2. Model description

A new interaction model designed to be applied in force feedback desktop haptic interfaces is introduced in this section. Removing the limitations of the workspace when using this kind of haptics for interaction in large virtual scenes is its main objective.

The model can be classified within the group of position control based techniques and it pursues a higher level of simplicity, speed and precision for the user when using a force feedback desktop haptic interface for interaction in computer-generated virtual environments.

The proposed interaction model is based on the realization of a series of amplifi-

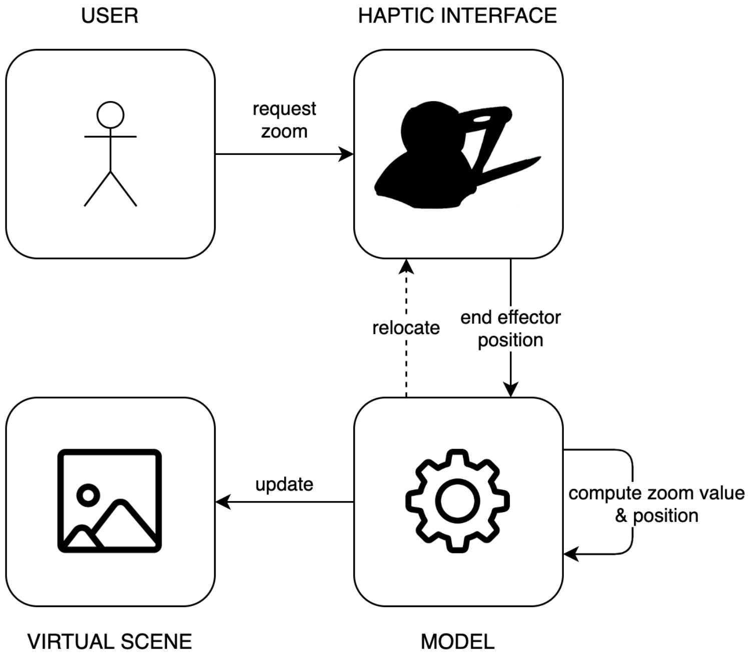


Figure 1. Operation diagram of the interaction model.

cations on the initial scene using the position of the virtual avatar of the haptic as reference. In each of the generated scenes, the direct or scaled mapping technique is applied, so that the virtual avatar can reach any point of the scene within the available workspace. This model is called Haptic Zoom and it allows the user to interact with the scene by using a haptic device on which the direct or scaled mapping technique is applied. This way, when higher precision is required in a certain area, the haptic zoom can be activated. Once activated, the original scene is translated into an amplified version of it. When this second scene is generated, a remapping (or rescaling) of the movement factor of the device is applied, so that, again, any point in the scene may be reached within the available workspace.

How the proposed model works is schematically represented in Figure 1. The user, through the haptic device, requests a scene amplification. The haptic device is in charge of transmitting the order towards the interaction model as well as the end-effector position inside the workspace. The interaction model computes the new level of zoom and the new position that must be applied to the scene. In order to obtain these new values, the preconfigured parameters and the data received from the haptic device are used. Finally, the model updates the scene based on the values obtained throughout the process.

The model must also update the haptic device end-effector based on the chosen location for the amplification, as is explained in detail in Section 2.2.2.

2.2.1. Zoom Modes

Two ways of carrying out an amplification in a scene are considered in the model: constant amplification and progressive amplification.

(1) **Constant amplification.** The constant amplification mode is based on the

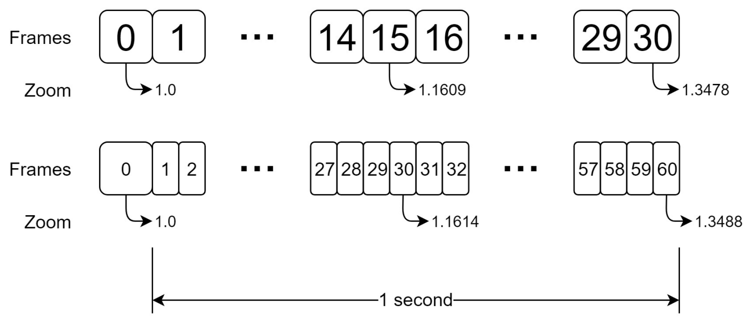


Figure 2. One second of progressive amplification example at 30 and 60 fps.

definition of a scale factor. This factor will be added to or subtracted from the current zoom level of the scene depending on whether the user wants to scale the zoom level of the scene up or down. The scale factor is preconfigured in the application controlling the process.

The general formula which is applied for the calculation of the amplification level of a generic scene is detailed in Equation 1, in which a_i represents the amplification level that will be applied to scene i and a_{i-1} the amplification level applied to the previous scene.

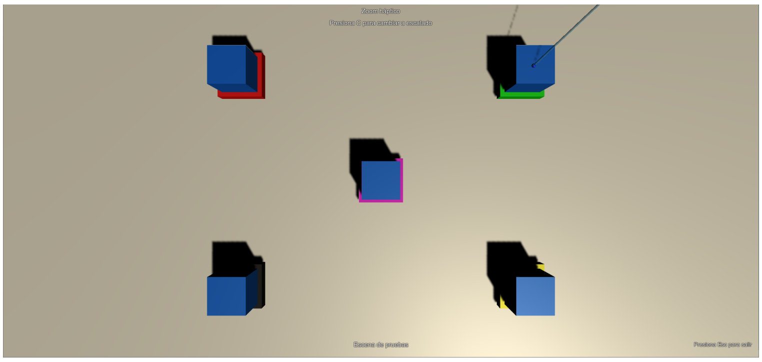
$$a_i = a_{i-1} \pm scale\_factor \tag{1}$$

(2) **Progressive amplification.** The progressive amplification mode is based on performing a large number of amplifications in a short period of time, resulting in a smooth amplification process. As in constant amplification mode, a scale factor working as seed that allows calculating the corresponding amplification level is also needed. Additionally, it is necessary to establish the refresh rate that will be applied in the scenes in frames per second (fps). The minimum value for obtaining a smooth amplification is 30 fps, with 60 fps or more being the desirable value.

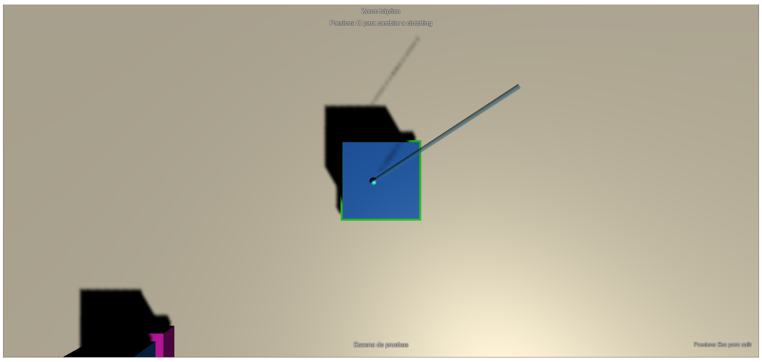
In progressive amplification mode the general formula which is applied for the calculation of the amplification level of a generic scene is detailed in Equation 2.

$$a_i = a_{i-1} \pm \frac{scale\_factor * a_{i-1}}{fps} \tag{2}$$

The calculation of the amplification level for sequential scenes during 1 second in progressive amplification mode is shown in Figure 2. Refresh rates of 30 fps and 60 fps are included. Due to the weight of the refresh rate in the formula, a small variation of the amplification level in 1 second can be observed when applying a refresh rate of 30 fps or 60 fps. This means that a faster amplification will be achieved with a higher refresh rate of the scenes. This difference is not considered significant because the weight of the scale factor in the formula is the one that determines the generated amplification levels.



(a) Scene at original amplification level.



(b) Scene following amplification.

Figure 3. Haptic zoom example with point-centered amplification.

2.2.2. Zoom Location

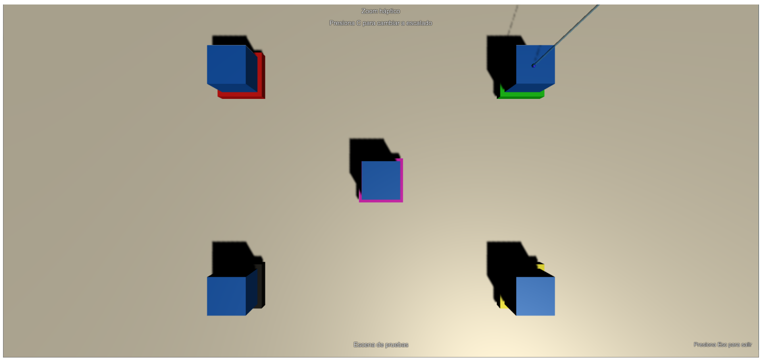
The proposed model contemplates two ways of carrying out the corresponding amplifications based on the position of the virtual avatar of the device:

(1) **Pointer-centered amplification.** This method records the position of the haptic virtual avatar the moment the zoom is executed and makes it the center of the resulting scene. This implies the need to recenter the end-effector of the haptic device in its work area by applying a force fixing the end-effector to the center of its workspace in order to maintain concordance with its on-screen representation.

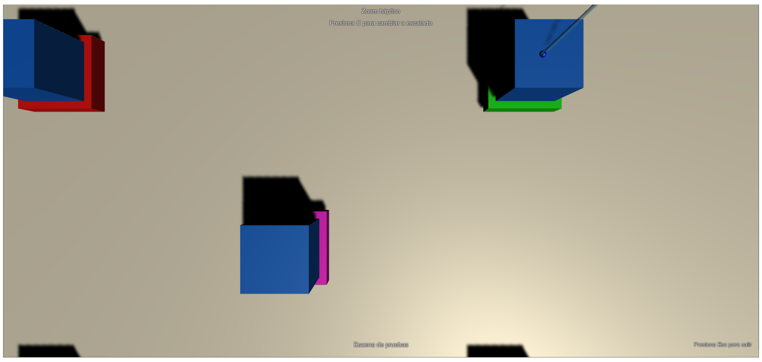
Figure 3 shows an example of point-centered amplification in which 3a shows the scene with the original level of amplification (1.0). The avatar is located in the region of interest (i.e., top right cube). 3b shows the resulting scene after the point-centered amplification and end-effector relocation are applied.

(2) **Amplification maintaining proportions.** This method executes the amplification in a way that the virtual avatar maintains a distance from the limits of the scene that is proportional to the original one, meaning that no physical relocation of the end-effector is needed, avoiding in this way the lack of naturalness perceived by the user when the end-effector relocates itself in the center of the workspace. This is the preferred amplification mode.

Figure 4 depicts an example of amplification maintaining proportions in which 4a shows the scene with the original level of amplification (1.0). The avatar is located in the region of interest (i.e., top right cube). 4b shows the resulting scene after the amplification maintaining proportions is applied. As in point-centered



(a) Scene at original amplification level.



(b) Scene following amplification.

Figure 4. Haptic zoom example with amplification maintaining proportions.

amplification the avatar can be observed in the same location as in the previous figure but no forces have been applied to the end-effector in order to relocate it in the center of the workspace.

In the amplification maintaining proportions method, both scaling up and down the scene should be done with the avatar in the same location if coming back to the original scene is expected. The right sequence of actions is as follows:

(a) Recognize the scene and identify the area of interest without zooming.
(b) Amplify into the area of interest and perform the desired interaction.
(c) Scale down the scene to the original amplification level in order to identify the new area of interest.

2.2.3. Zoom Order

Different physical features are available in market-ready force feedback desktop haptic devices. Some of them are equipped with one, two or even more buttons within their end-effector, while other ones do not have any button. This situation must be taken into account from the proposed interaction model, allowing the user to execute the zoom order in a natural and convenient way—without an additional input device. Thus, three subgroups are contemplated, based on the number of buttons available in their end-effectors.

Desirable amplification activation modes, both constant and progressive amplification, based on the features of the haptic interface, are summarized in Table 1. If the device has at least one button, it will be used for zoom activation. When the device has

Table 1. Zoom activation based on haptic device button availability.

	Constant amplification	Progressive amplification
One button	The scene is scaled up by pressing the button. Scaling down the scene is performed by double pressing the button.	The scene is scaled up in a progressive way by pressing the button long. Progressively scaling down the scene is performed by quickly pressing the button followed by a long press.
Two or more buttons	The scene is scaled up by pressing one of the buttons. Scaling down the scene is performed by pressing another button.	The scene is scaled up in a progressive way by pressing one button long. Progressively scaling down the scene is performed by pressing another button long.
Without buttons	The user can apply the desired amplification level, either in constant or progressive mode, through preset voice commands.	

no buttons, voice commands will be used as the order for triggering both amplification mode and amplification level.

2.3. Evaluation

To compare our new interaction technique with those most commonly used in the context of desktop haptic devices, we have conducted an experiment based on two tasks: collecting coins and interacting with shapes in a maze.

2.3.1. Subjects

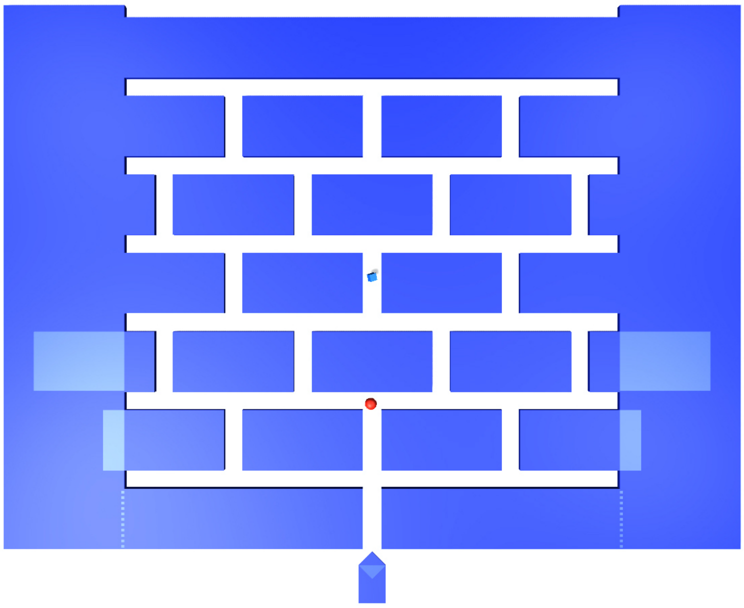
The population of the experiment was individuals with a computer science background and experienced in the use of haptic technology. A total of 5 women and 7 men aged between 21 and 50 years, with a computer science background of between 5 and 15 years, performed the evaluation.

2.3.2. Task

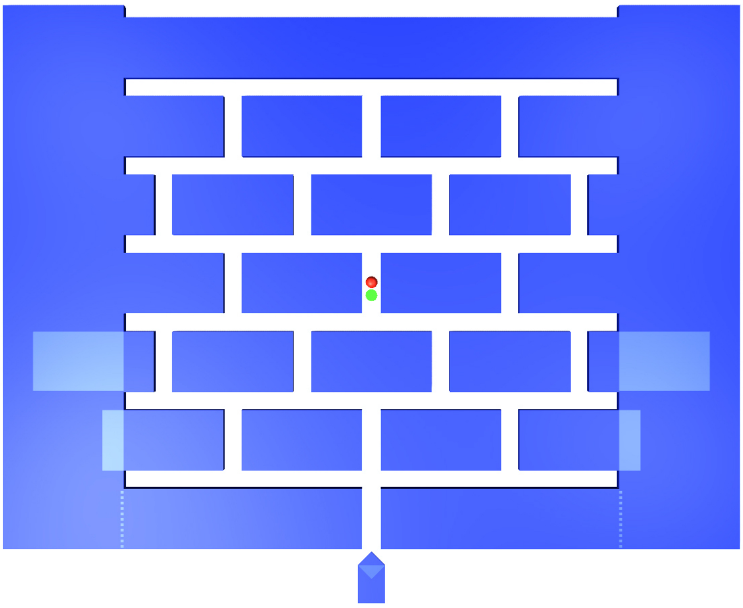
We selected a coin collecting task that requires both repositioning and touching in an accurate way in order to be completed successfully. The source code that includes the implementation of haptic zoom over Unity, as well as this task, is available in (Gutierrez-Fernandez, Fernandez-Llamas, Esteban, & Conde, 2020).

The task consists of reaching the points within a maze where a coin is spinning (see Figure 5). Both the walls and the floor of the maze can be touched and felt by the user. Two phases can be distinguished in each iteration: an approximation phase and an operation phase. In the approximation phase, the user has to reach the point within the maze where the coin is spinning without touching the walls of the maze (5a). Once the avatar touches the coin the second phase is activated. In the second phase, the operation phase, a circular shape (marker) appears near the collected coin (5b). The shape has a haptic effect attached, which the user has to guess. The possible associated haptic effects are: vibration effect, stickiness, roughness, magnet effect or absence of effect, all of them being randomly distributed among the markers. The user has to keep the avatar motionless in the center of the shape for three seconds in order to continue with the next coin. To complete the task, the user has to collect a total of five coins and overcome their corresponding markers.

For the experiment, three position control techniques were implemented and com-



(a) Coin spinning (blue cube).



(b) Marker with haptic effect (green circle).

Figure 5. Scene used for performing the evaluation.

pared in order to evaluate the potential effectiveness of haptic zoom. It has not been compared with any of the other techniques mentioned in related work either because of the need for special hardware for its implementation or because of the lack of transparency (Vlachos & Papadopoulos, 2006).

(1) **Direct mapping**. The direct mapping technique adjusts the haptic device workspace in order to fit to the scene dimensions. A scale factor is applied to the movements of the end-effector so that users are allowed to reach any point of the scene without any further action.
(2) **Clutching**. The clutching technique is based on a smaller workspace, in which users can move around the scene in order to reach any point of it. Users can declutch the movement of the avatar from the end-effector and place it in a more comfortable position while the avatar remains stationary. This action is typically carried out when the avatar is near the limits of the workspace. In our implementation, the workspace size while using the clutching technique is five times smaller than the scene dimensions. The declutching is activated while the user presses one of the haptic device buttons.
(3) **Haptic zoom**. Haptic zoom was implemented as described previously in Section 2.2. The two buttons from the Geomagic Touch haptic device allow us to implement the progressive amplification maintaining proportions; thus, while one button is pressed the scene is scaled up whereas while the other button is pressed the scene is scaled down. Users are not forced to perform the amplification but it is helpful to avoid collisions and easily distinguish the effects on markers.

2.3.3. Assessment instrument

To perform the tasks, participants used a standard desktop PC and a Geomagic Touch desktop haptic device (previously PHANToM Omni) from 3D Systems (SensAble). The experimental environment was developed as a simulator, using the Unity Engine combined with the 3D Systems Openhaptics®Unity Plugin; the latter to achieve haptic feedback.

First of all, participants were asked to read a brief summary of how the three interaction methods work. It must be noted that all participants had previous experience in the use of the direct mapping technique, two of them were familiar with clutching and none of them had used haptic zoom before. A test scene was presented in which participants could freely try the interaction techniques by using a scene different from the one selected for the evaluation. This previous phase not only allowed participants to put into practice the theory they had just read about, but also to see how each one of the methods works. Then, the main task was explained and if they did not have any questions about it, the experiment started (see Figure 6). The order in which the three methods were evaluated was randomly calculated in order to avoid a training effect.

The experiment ended with a subjective questionnaire (see Table 2) called USE questionnaire (Lund, 2001), used to evaluate four dimensions: usefulness, ease of use, ease of learning and satisfaction. Users were asked to rate their degree of agreement with the statements from one to seven, ranging from *strongly disagree* to *strongly agree*. Some of the questions are marked as less significant in the questionnaire, so a total of 20 questions were chosen from the original 27 questions. Those questions left out do not adjust to our experiment. Furthermore, a final question, in which users had to state their general opinion about the three evaluated methods, was added.

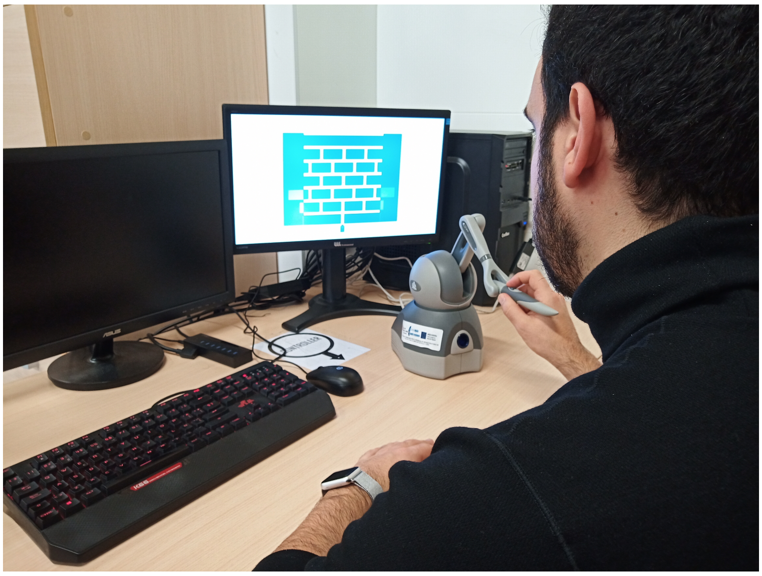


Figure 6. Expert performing the evaluation.

Table 2. Subjective questionnaire.

Dimension	**Statement**
Usefulness	It is useful It helps me be more effective It helps me be more productive It gives me more control over the activity It makes the things I want to accomplish easier to get done It saves me time when I use it It does everything I would expect it to do
Ease of use	It is easy to use It is simple to use It is user friendly It requires the fewest steps possible to accomplish what I want to do with it Using it is effortless I can use it without written instructions I don't notice any inconsistencies as I use it I can recover from mistakes quickly and easily
Ease of learning	I learned to use it quickly I easily remember how to use it It is easy to learn to use it I quickly became skillful with it
Satisfaction	I am satisfied with it
Final question	My general opinion about the method

Table 3. Data collected from each evaluation.

Perf. indicator	Description
time	Time needed to perform the task in seconds
repositioning time	Time spent repositioning the avatar towards the coins
wall errors	Total number of maze wall touches while performing the task
marker errors	Total number of tries to overcome each marker, defined as the number of times the three second counter is reset
marker times	Time elapsed between each marker appearing and the user overcoming them
distance	Total distance covered by the avatar during the task
marker effects	User description about the felt haptic effect in each one of the markers

2.3.4. Collected data

Seven items were collected for each expert while using each of the three techniques (see Table 3). Only the *markers effects* that users said they had felt were noted manually by one of the authors while the other six performance indicators were recorded automatically by the software developed for the evaluation. Each one of the participants filled out the questionnaire electronically after completing the tasks with all the techniques.

All data collected is accessible in (Gutierrez-Fernandez, Fernandez-Llamas, Esteban, & Conde, 2022).

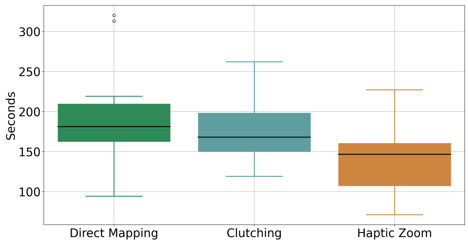
3. Results

This section presents the results of the statistical analysis carried out on both the quantitative data and the answers to the questionnaire collected in the evaluation.

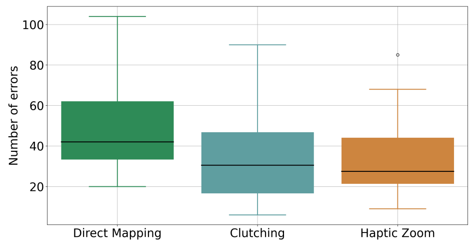
3.1. Performance indicators

As it is not possible to determine if the variables are normally distributed due to the small number of participants who took part in the experiment, a non-parametric statistical test to check the differences among the three methods has been chosen. We computed a Kruskal-Wallis test (Kruskal & Wallis, 1952) on five performance indicators: *time*, *wall errors*, *marker errors*, *marker times* and *distance*. The between participants factor was the method used during the evaluation (direct mapping, clutching and haptic zoom).

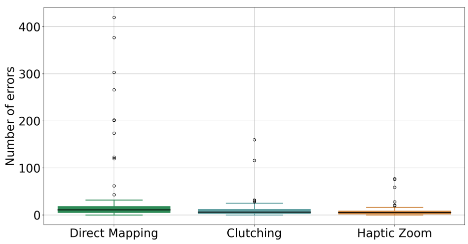
No statistically significant trend was observed in *time* ($p = 0.05024 > 0.05$, $\chi^2 = 5.9819$, $df = 2$) or *wall errors* ($p = 0.2238 > 0.05$, $\chi^2 = 2.994$, $df = 2$) indicators (see Figures 7a and 7b). Regarding the indicators concerning the markers, both *marker errors* and *marker times* showed a statistically significant trend ($p = 0.000896 < 0.05$, $\chi^2 = 14.035$, $df = 2$; and $p = 0.001367 < 0.05$, $\chi^2 = 13.19$, $df = 2$ respectively). The medians of *marker errors* were 11 for direct mapping, 6 for clutching and 5 for haptic zoom (see Figure 7c), whereas the medians for *marker times* were 18, 13.5 and 11 respectively (see Figure 7d). It is worth noting that the statistical analysis on both *marker errors* and *marker times* performance indicators has been made with the error and time values for each of 5 markers for the 12 participants (60 entries in total). For instance, it took 2 minutes for one of the participants to get through one of the markers using the direct mapping technique, making a total of 420 errors



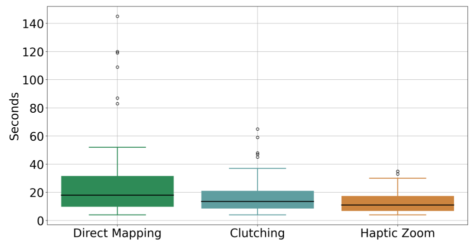
(a) Time.



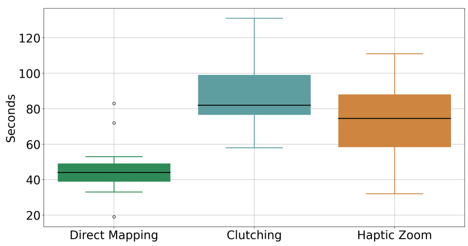
(b) Wall errors.



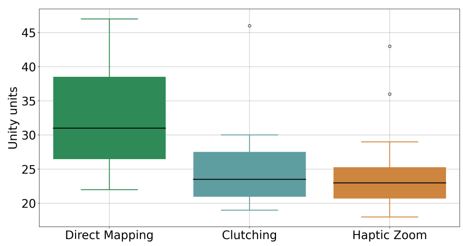
(c) Marker errors.



(d) Marker times.



(e) Repositioning time.



(f) Distance.

Figure 7. Raw data representation.

in the process. The *repositioning time* indicator also showed a statistically significant trend ($p = 0.0006575 < 0.05$, $\chi^2 = 14.654$, $df = 2$) with median values of 44 for direct mapping, 82 for clutching and 74.5 for haptic zoom (see Figure 7e). Finally, the *distance* indicator showed a statistically significant trend also ($p = 0.01741 < 0.05$, $\chi^2 = 8.1015$, $df = 2$) with medians of 31, 23.5 and 23 for direct mapping, clutching and haptic zoom respectively (see Figure 7f).

A post-hoc Dunn's test with Holm's correction method was computed in order to identify those pairs of techniques with statistical differences. These pairwise comparisons indicated that, for each performance indicator, direct mapping scores were observed to be significantly different from those of haptic zoom (*marker errors* $\rightarrow$ $p < 0.001$; *marker times* $\rightarrow p < 0.001$; *repositioning time* $\rightarrow p = 0.008$; and *distance* $\rightarrow p = 0.013$) and clutching (*marker errors* $\rightarrow p = 0.012$; *marker times* $\rightarrow p = 0.039$; *repositioning time* $\rightarrow p < 0.001$; and *distance* $\rightarrow p = 0.021$). No statistically significant trend was observed between clutching and haptic zoom in any performance indicator (*marker errors* $\rightarrow p = 0.116$; *marker times* $\rightarrow p = 0.055$; *repositioning time* $\rightarrow p = 0.132$; and *distance* $\rightarrow p = 0.379$).

The last performance indicator, *marker effects*, was analyzed based on the number of correct answers given by participants about the effect felt. The percentages of correct answers were 45% for direct mapping, 51.67% for clutching and 61.67% for haptic zoom. Moreover, a binomial test was performed in order to check if there are statistical differences between the pairs of techniques. The comparison of clutching, both with direct mapping and with haptic zoom, showed no statistically significant trend ($p = 0.369$ and $p = 0.113$ respectively); although a statistically significant trend was observed between direct mapping and zoom ($p = 0.011$).

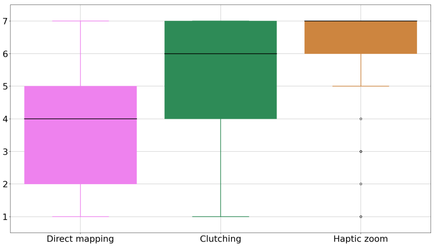
3.2. Questionnaire

Data obtained from the questionnaire was analyzed using the Wilcoxon signed-rank test. Haptic zoom scores were observed to be significantly different from those of direct mapping ($p < 0.001$) and clutching ($p < 0.001$). No statistically significant trend was found between direct mapping and clutching ($p = 0.646$). Analyzing the scores by dimension, a statistically significant trend has been observed in terms of usefulness ($p < 0.001$ for the three pairs of techniques) (see Figure 8a). In the ease of use and ease of learning dimensions, a statistically significant trend when comparing clutching with direct mapping and haptic zoom ($p < 0.001$ on both for the two dimensions) has also been observed. No statistical difference has been found in terms of ease of use and ease of learning between direct mapping and haptic zoom ($p = 0.132$ and $p = 0.468$ respectively) (see Figures 8b and 8c). Finally, no statistically significant trend was observed between any pair of techniques in terms of satisfaction ($p = 0.632$ for direct mapping / clutching pair; $p = 0.081$ for direct mapping / haptic zoom pair; and $p = 0.116$ for clutching / haptic zoom pair) (see Figure 8d).

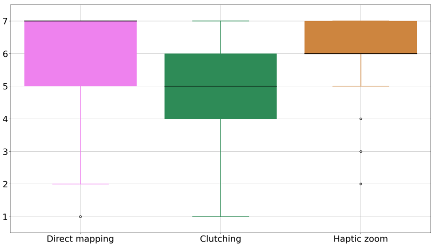
4. Discussion

The performance results shown above indicate that the new haptic zoom interaction technique can help in situations in which both relocation freedom and local accuracy are required.

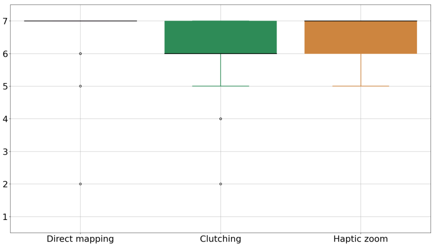
No differences were found in terms of *time* and *wall errors*, but the differences among the three methods found in terms of *markers errors* show that haptic zoom



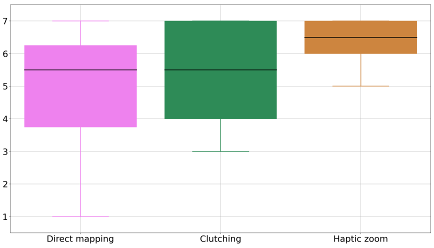
(a) Usefulness.



(b) Ease of use.



(c) Ease of learning.



(d) Satisfaction.

Figure 8. Score obtained by each method for each dimension of the subjective questionnaire for a population of N=12

.

and clutching techniques are more accurate at points of interest than direct mapping technique, as can be clearly seen in Figure 7c by the number of outliers. The *markers time* indicator also shows a difference between techniques, with direct mapping becoming a time-consuming technique when the task is related to accuracy. The *distance* is a differentiating indicator as well, as haptic zoom and clutching are the methods that make users travel shorter distances. In terms of *repositioning time*, direct mapping scores the best with haptic zoom and clutching techniques lagging behind. Ignoring the displacement itself, this can be justified by the requirement of having to perform additional actions for repositioning the avatar ("declutch-clutch" for the clutching technique and "zoom in-out" for the haptic zoom technique), actions that are not necessary in the direct mapping technique.

Regarding the effects felt by participants while performing the evaluation, haptic zoom yielded a 61.67% correct answer rate. This is significantly higher than direct mapping (45%) and slightly better than the clutching technique (51.67%) although this difference is not statistically significant. However, this is far from what was expected for direct mapping and clutching (as these two techniques are focused on *accuracy*). It can be explained by the effects chosen to identify or by the small region in which the effects were applied. Some users suggested a previous training phase in which effects are explained and practiced.

On the other hand, the analysis of the answers given by the participants in the subjective questionnaire shows significant differences among the three techniques in several of the dimensions that have been considered. In terms of usefulness, the haptic zoom technique is clearly superior to clutching and direct mapping. Regarding ease of use and ease of learning dimensions, the results show that our new technique is as easy to use and learn as direct mapping, the simplest and most widely used technique in the field of force feedback desktop haptic devices. This fact also implies that haptic zoom is clearly differentiated from clutching in these two dimensions. This is a great advantage for the new technique, which was paired with clutching in the analysis done so far. Furthermore, no differences in terms of satisfaction were found among the three analyzed techniques.

Finally, the data collected from the general opinion question about the three methods show some interesting insights. Direct mapping is usually described by users as a "very tough method when accuracy is needed" but an "easy method for navigating in the scene". Clutching is described as a "more difficult method to learn than direct mapping and haptic zoom, but once you got it, it is useful". And haptic zoom is described as "the best method for both navigation and accuracy tasks but with the problem of having to zoom in and out in the same place".

4.1. Conclusion

A new force feedback desktop haptic device interaction technique has been presented. It is called *haptic zoom* and through scene amplifications and workspace remappings, it allows users both to relocate the avatar to the desired point in the scene and to interact with a high level of accuracy at this point.

An evaluation of this new technique has been carried out, comparing haptic zoom with two well-known position control desktop haptic device techniques—direct mapping and clutching. Results showed that haptic zoom is better than direct mapping and is as good as clutching in terms of local accuracy and travel distance. Besides, haptic zoom is equivalent to clutching in allowing users to feel through the sense of touch what they are interacting with. Regarding the usability, haptic zoom scores exceed direct mapping and clutching, helping users in getting closer to their goals (usefulness), and is at the same level as direct mapping in use and learning ease. This is the key differentiating factor between haptic zoom and clutching and it shows that this new interaction technique combines the best of direct mapping and clutching in a single technique. Experts have provided good feedback about this new interaction technique too, and, overall, they find it very useful and promising.

Although with just twelve users for the evaluation a statistically significant study has been performed, a more complete empirical evaluation with a higher number of participants with different backgrounds is planned as future work. We expect good results for haptic zoom in this next evaluation, based on the promising results obtained in this evaluation.

Acknowledgements

A. G. acknowledges a FPU fellowship provided by the Ministerio de Educación, Cultura y Deporte of Spain.

The authors would also like to thank all experts who participated the evaluation for their time.

Disclosure statement

We have no conflicts of interest to disclose.

References

Burdea, G. C. (2000). Haptics issues in virtual environments. In *Computer graphics international, 2000. proceedings* (pp. 295–302).

Chouvardas, V. G., Miliou, A. N., & Hatalis, M. K. (2008). Tactile displays: Overview and recent advances. *Displays*, *29*(3), 185–194.

Conti, F., & Khatib, O. (2005). Spanning large workspaces using small haptic devices. In *First joint eurohaptics conference and symposium on haptic interfaces for virtual environment and teleoperator systems. world haptics conference* (pp. 183–188).

Dominjon, L., Lecuyer, A., Burkhardt, J.-M., Andrade-Barroso, G., & Richir, S. (2005). The" bubble" technique: interacting with large virtual environments using haptic devices with limited workspace. In *Eurohaptics conference, 2005 and symposium on haptic interfaces for virtual environment and teleoperator systems, 2005. world haptics 2005. first joint* (pp. 639–640).

Dominjon, L., Perret, J., & Lécuyer, A. (2007). Novel devices and interaction techniques for human-scale haptics. *The Visual Computer*, *23*(4), 257–266.

Fischer, A., & Vance, J. M. (2003). Phantom haptic device implemented in a projection screen virtual environment. In *Proceedings of the workshop on virtual environments 2003* (pp. 225–229). New York, NY, USA: ACM. Retrieved from http://doi.acm.org/10.1145/769953.769979

Force dimension omega haptics. (n.d.). https://www.forcedimension.com/products.

Giri, G. S., Maddahi, Y., & Zareinia, K. (2021). An application-based review of haptics technology. *Robotics*, *10*(1), 29.

Gu, X., Zhang, Y., Sun, W., Bian, Y., Zhou, D., & Kristensson, P. O. (2016). Dexmo: An inexpensive and lightweight mechanical exoskeleton for motion capture and force feedback in vr. In *Proceedings of the 2016 chi conference on human factors in computing systems* (pp. 1991–1995).

Gutierrez-Fernandez, A., Fernandez-Llamas, C., Esteban, G., & Conde, M. A. (2020). *Haptic zoom interaction technique implementation for unity.* https://github.com/uleroboticsgroup/haptic-zoom.

Gutierrez-Fernandez, A., Fernandez-Llamas, C., Esteban, G., & Conde, M. A. (2022). *Haptic zoom: An interaction model for desktop haptic devices with limited workspace - evaluation data.* https://doi.org/10.5281/zenodo.5950721.

Helpmesee eye surgery simulator. (n.d.). https://www.moog.com/content/sites/global/en/markets/medical-dental-simulation/eye-surgery-simulator.html.

Hirzinger, G., Brunner, B., Dietrich, J., & Heindl, J. (1993). Sensor-based space robotics-rotex and its telerobotic features. *IEEE Transactions on robotics and automation*, *9*(5), 649–663.

Hollis, R. L., & Salcudean, S. E. (1993). Lorentz levitation technology: a new approach to fine motion robotics, teleoperation, haptic interfaces, and vibration isolation rl hollis se salcudean. In *Proc. fifth intl symp. robotics research* (pp. 1–18).

Hou, I. A., & Srinivasan, M. A. (1998). *Multimodal virtual environments: Magic toolkit and visual-haptic interaction paradigms* (Tech. Rep. No. 8 - RLE TR-620). Touch Lab, Massachusetts Institute of Technology, MIT.

Kitchenham, B. A., Budgen, D., & Brereton, P. (2015). *Evidence-based software engineering and systematic reviews* (Vol. 4). CRC press.

Kruskal, W. H., & Wallis, W. A. (1952). Use of ranks in one-criterion variance analysis. *Journal of the American Statistical Association*, *47*(260), 583–621.

Li, Z., Akkil, D., & Raisamo, R. (2019). Gaze augmented hand-based kinesthetic interaction: What you see is what you feel. *IEEE transactions on haptics*, *12*(2), 114–127.

Liu, L., Liu, G., Zhang, Y., & Wang, D. (2014). A modified motion mapping method for haptic device based space teleoperation. In *The 23rd ieee international symposium on robot and human interactive communication* (pp. 449–453).

Loomis, J. M., & Lederman, S. J. (1986). Tactual perception. *Handbook of perception and human performances*, *2*, 1–41.

Lund, A. M. (2001). Measuring usability with the use questionnaire12. *Usability interface*, *8*(2), 3–6.

Magnuson, C., & Rassmus-Gröhn, K. (2003). Non-visual zoom and scrolling operations in a virtual haptic environment. In *Proc. eurohaptics.*

Massie, T. H., Salisbury, J. K., et al. (1994). The phantom haptic interface: A device for probing virtual objects. In *Proceedings of the asme winter annual meeting, symposium on haptic interfaces for virtual environment and teleoperator systems* (Vol. 55, pp. 295–300).

Minamizawa, K., Kamuro, S., Fukamachi, S., Kawakami, N., & Tachi, S. (2008). Ghostglove: Haptic existence of the virtual world. In *Acm siggraph 2008 new tech demos* (pp. 18:1–18:1). New York, NY, USA: ACM. Retrieved from http://doi.acm.org/10.1145/1401615.1401633

Pacchierotti, C., Sinclair, S., Solazzi, M., Frisoli, A., Hayward, V., & Prattichizzo, D. (2017). Wearable haptic systems for the fingertip and the hand: taxonomy, review, and perspectives. *IEEE transactions on haptics*, *10*(4), 580–600.

Pavlik, R. A., Vance, J. M., & Luecke, G. R. (2013). Interacting with a large virtual environment by combining a ground-based haptic device and a mobile robot base. In *International design engineering technical conferences and computers and information in engineering conference* (Vol. 55867, p. V02BT02A029).

Rastogi, R., & Pawluk, D. T. (2013). Toward an improved haptic zooming algorithm for graphical information accessed by individuals who are blind and visually impaired. *Assistive Technology*, *25*(1), 9–15.

Richard, G., Pietrzak, T., Argelaguet, F., Lécuyer, A., & Casiez, G. (2021). Studying the role of haptic feedback on virtual embodiment in a drawing task. *Frontiers in Virtual Reality*, *1*, 28.

Riener, R., & Harders, M. (2012). Haptic aspects. In *Virtual reality in medicine* (pp. 79–129). London: Springer London.

Rodríguez, J.-L., Velázquez, R., Del-Valle-Soto, C., Gutiérrez, S., Varona, J., & Enríquez-Zarate, J. (2019). Active and passive haptic perception of shape: Passive haptics can support navigation. *Electronics*, *8*(3), 355.

Schneider, O., MacLean, K., Swindells, C., & Booth, K. (2017). Haptic experience design: What hapticians do and where they need help. *International Journal of Human-Computer Studies*, *107*, 5–21.

Simodont dental simulator. (n.d.). http://www.nissin-dental.net/products/DentalTrainingProducts/DentalSimulator/simodont/index.html.

Srinivasan, M. A., & Basdogan, C. (1997). Haptics in virtual environments: Taxonomy, research status, and challenges. *Computers & Graphics*, *21*(4), 393–404.

Vlachos, K., & Papadopoulos, E. (2006). Transparency maximization methodology for haptic devices. *IEEE/ASME Transactions on Mechatronics*, *11*(3), 249–255.

Ziat, M., Gapenne, O., Stewart, J., Lenay, C., & Bausse, J. (2007). Design of a haptic zoom: levels and steps. In *Second joint eurohaptics conference and symposium on haptic interfaces for virtual environment and teleoperator systems (whc'07)* (pp. 102–108).

Notes on contributors

Alexis Gutiérrez-Fernández received his Computer Science Degree in 2016 and his Computer Science Master in 2018. He is now working on his PhD thesis seeking to merge the senses of sight and touch in the same virtual reality experiences through the use of virtual reality head-mounted displays and haptic interfaces.

Camino Fernández-Llamas has extensive experience in Computer Science and has coordinated and participated in more than twenty European and national research projects in her twenty-three years of experience after getting a degree in Computer

Science, a Master's degree in Knowledge Engineering and a PhD from the Universidad Politécnica de Madrid.

Gonzalo Esteban received a Bachelor of Engineering degree in Computer Science, a Master's degree in Cybernetic Research and a PhD degree from the University of León, Spain, in 2009, 2011 and 2020, respectively. Since 2017, he has been working as a Research Assistant at the same university. His research interests include computer haptics and cybersecurity.

Miguel Á. Conde received his MSc (2008) and PhD (2012) from the University of Salamanca (Spain). From 2010 to 2012 he researched at the University of Salamanca and also worked there as a lecturer. Presently he works as an assistant professor at the University of León, which he joined in 2013.