

A Survey on Bimanual Haptic Interaction

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Abstract—When interacting with virtual objects through haptic devices, most of the time only one hand is involved. However, the increase of computational power, along with the decrease of device costs, allow more and more the use of dual haptic devices. The field which encompasses all studies of the haptic interaction with either remote or virtual environments using both hands of the same person is referred to as bimanual haptics. It differs from the common unimanual haptic field notably due to specificities of the human bimanual haptic system, *e.g.* the dominance of the hands, their differences in perception and their interactions at a cognitive level. These specificities call for adapted solutions in terms of hardware and software when applying the use of two hands to computer haptics. This paper reviews the state of the art on bimanual haptics, encompassing the human factors in bimanual haptic interaction, the currently available bimanual haptic devices, the software solutions for two-handed haptic interaction, and the existing interaction techniques.

Index Terms—Haptics, bimanual interaction



1 INTRODUCTION

IN our daily lives, we commonly use both of our hands to perform all sorts of tasks. Holding a bottle with a hand while opening it with the other, holding the steering wheel while changing gears when driving, keeping the right orientation of a nail while hammering it... A fair amount of these tasks are performed in a bimanual way so naturally that we sometimes do not even pay attention to the fact that we use two hands in the process. When it comes to haptic interaction with either virtual or remote environments, until recently the interaction happened mostly through one hand only, generally the one referred to as the “dominant hand”. Considering the importance of bimanual interaction in real life, not using both of our hands could lead to a loss of efficiency or immersion for a certain number of tasks. This raises the need to integrate the use of two hands in haptics.

Bimanual haptics refers to haptic interaction through both hands of the same person (example in Figure 1). This form of interaction is more specific than the general *multi-touch* or *multi-finger* kinds in that the latter do not necessarily involve both hands. It also differs from *multi-user* interaction as it involves multiple hands, but not necessarily of the same person. Bimanual interaction bears some specific properties at a cognitive level that the other forms of interaction lack. In this paper, we emphasize these unique characteristics to illustrate what benefits bimanual haptics can provide over those, as well as desirable characteristics for bimanual haptic hardware, software and interaction techniques.

This domain of two-handed haptics is starting to emerge, notably with the increase of computational power available and the decrease of costs of haptic devices, but also with an increasing number of studies focusing on this topic. This paper reviews the current state of studies on bimanual haptics and discusses the current perspectives in this field. The paper is structured so as to follow the different steps that allow a user to perform a bimanual task in a virtual or remote environment (Figure 2). First, we describe the cognitive mechanics of bimanual interaction. We then present the current state of the art on bimanual haptic hardware, software and interaction techniques. Finally, we conclude with current applications and perspectives of this field.



Fig. 1. An example of bimanual haptics: preparing virtual crepes with a virtual bowl and pan, with force feedback on both hands [1].

2 BIMANUAL HAPTIC INTERACTION

Working with two hands is not simply “using twice one hand”. First of all, there are clear differences between the way both hands function, notably relative to each other, as we have a dominant hand (DH) and a non-dominant hand (NDH). Then, the use of two

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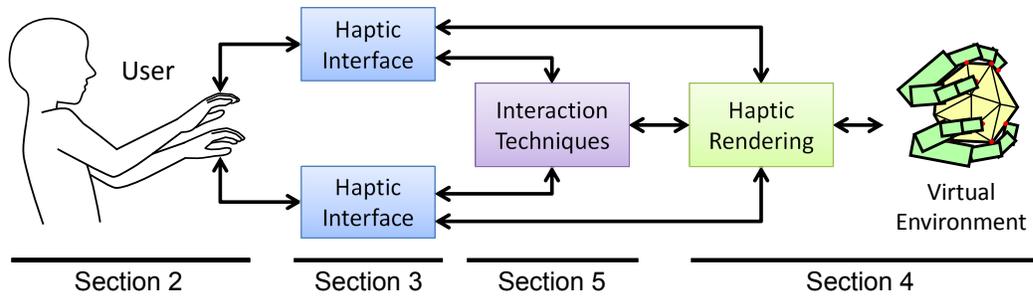


Fig. 2. Different steps allowing a user to perform a bimanual haptic task in a virtual or remote environment. The user (human layer) interacts with the haptic interfaces (hardware layer), which are coupled to the virtual environment through haptic rendering (software layer). Interaction techniques are linked to all of these elements and further allow the user to perform a given task.

hands acting in an integrated way allows to perform tasks that could hardly be done with a single hand, or with hands working on independent subtasks that involve no interaction between both hands. Finally, there are additional haptic cues provided by the joint use of two hands.

This section deals with the cognitive and motor aspects of the use of two hands, by first focusing on the benefits of bimanuality over unimanuality. We then review some key observations on bimanual cognition, motor action, and haptic perception.

2.1 Bimanual Haptic Perception

Bimanual actions involve a major form of haptic feedback: the ability to locate our hands relatively to each other. While the presence of visual feedback causes the visual sense to be predominantly used over the haptic sense, this bimanual proprioception fully comes in action when this visual feedback is absent, inconsistent or incomplete [2], [3]. A notable example is that of blind people, for whom two-handed exploration represents a valuable means of estimating distances with their environment. Several studies showed that it is easier to follow the relative position between the hands rather than their individual position relatively to a 3D space [2], [3], [4], [5].

Some studies have also showed a certain level of specialization of the hands when it comes to haptic perception. It was suggested that the NDH has increased proprioceptive sensitivity, whether for right-handers [6] or left-handers [7]. This fact may be correlated with studies suggesting a specialization of the non-dominant hemisphere for proprioception processing [8], [9]. Brain studies also suggest that the parietal lobe is involved in the integration of sensorimotor information, and among other things for spatial perception [10]. Unilateral damage to this lobe has been shown to lead to a neglect of stimuli on the contralateral side of the lesions [11].

The integration of different stimuli between both hands was also studied. Concerning the haptic perception of curvature, while a similar discrimination

threshold for unimanual and bimanual curvature perception has been reported [12], [13], a more recent study actually observed a lower threshold for bimanual exploration of large cylinders [14]. This latter study clearly showed that this better discrimination is entirely due to integration of curvature perception between the two hands, as further experiments proved that the position discrimination has similar thresholds with one or two hands in this scenario. The bimanual perception of stiffness was shown to be more precise than unimanual stiffness perception, and that the bimanual perception was the result of the combination of both unimanual inputs in a statistically optimal manner [15]. Ballesteros *et al.* reported a better perception of symmetric shapes with bimanual exploration than unimanual, but not for perception of asymmetric shapes [16]. They also did not observe any significant difference of perception between the DH and NDH.

2.2 Bimanual Motor Control

The mechanisms that link the sensation in both hands to the motor control of these hands mostly remain to be studied. Experiments involving reaching tasks with each hand suggested transfers of learning between both hands [17], [18] as well as haptic information, with trajectory information transferred from the NDH to the DH, and endpoint position information transferred from the DH to the NDH [18], [19], [20]. Brain studies further suggest the existence of neural pathways that mediate the coordination of both hands during bimanual tasks [21].

A topic that has received considerable attention when it comes to two-handed interaction is the sequence of action during a bimanual task, for which the most common model is Guiard's Kinematic Chain model [22]. It makes an analogy of the DH and the NDH as two motors assembled in series, based on three major principles:

- 1) The NDH is a frame of reference for the DH.
- 2) The NDH precedes the DH in action.

- 3) Both hands act at different temporal and spatial scales, the NDH acting at a coarser scale.

The Kinematic Chain model applies to many real life tasks, such as sewing, which involves both hands. Handwriting is another example, where the DH moves the pen relatively to the paper, which is itself moved by the NDH relatively to the table [22]. It was demonstrated that this model can be used effectively for reasoning about precision manipulation tasks [23], as well as for designing two-handed interaction techniques [24], [25]. Ullrich *et al.* evaluated the first principle of the model (frame of reference concept) for interaction tasks with haptics through a virtual needle insertion task [26]. The needle was manipulated by the DH and to be inserted in a target, and the NDH could be assigned an asynchronous pointing task, having it touching another target close to the first one. This allows the creation of a frame of reference between the DH and NDH, and was shown to reduce significantly the completion times of the task without affecting precision.

Aside from Guiard’s model, another observed property of bimanual action is the degree of symmetry used when performing increasingly difficult tasks, such as tasks that are more cognitively demanding, that need to be executed faster, or more precisely. Bimanual tasks can be performed either symmetrically, in which case both hands will perform the same task (*e.g.* rope skipping), or asymmetrically, where both hands perform different tasks (*e.g.* striking a match). Additionally, they can be performed synchronously, meaning the motions of both hands are in phase (*e.g.* weight lifting), or asynchronously, with antiphase movements of both hands (*e.g.* rope climbing) [22], [27]. Hinckley *et al.* suggested that, for easy tasks, there is little asymmetry of the hands, while harder tasks, notably requiring more precision, induce a stronger specialization of the hands, meaning that they take more specific, non-interchangeable roles [23]. Further studies on a symmetric bimanual tracking task showed that increasing difficulty, necessity of dividing attention or lack of visual integration lead to a more sequential way of performing tasks as well as a slightly decreased parallelism (defined as the ratio of error rates between DH and NDH) [27]. Ulinski *et al.* experimented on bimanual selection techniques and reported better accuracy with symmetric techniques, while suggesting that asymmetric techniques are more suitable for tasks that are more cognitively demanding or that last for longer periods of time [28].

2.3 Bimanual Cognition

An important cognitive aspect in bimanual interaction is the notion of *task integration*, *i.e.* the compilation at a cognitive level of different subtasks into a single task, which can happen at three different levels [29]. First, it can consist of visual integration, like for instance

when scaling a rectangle by sliding its corners [30]. Then, there is motor integration, when different subtasks are combined into a single gesture [31]. Finally, there is conceptual integration, which causes the user not to think of an activity as a set of subtasks but rather as a single task, such as with a 3D cross-section visualization task [4], [5] (Figure 3). Such a task requires, unimanually, to shift between a “moving the view” task and a “moving the cutting plane” task, thus creating a third “change states” extraneous subtask. Using two hands, on the contrary, integrates these tasks into a single “cut relative to view” meta-task, which is performed in a single gesture (Figure 3).

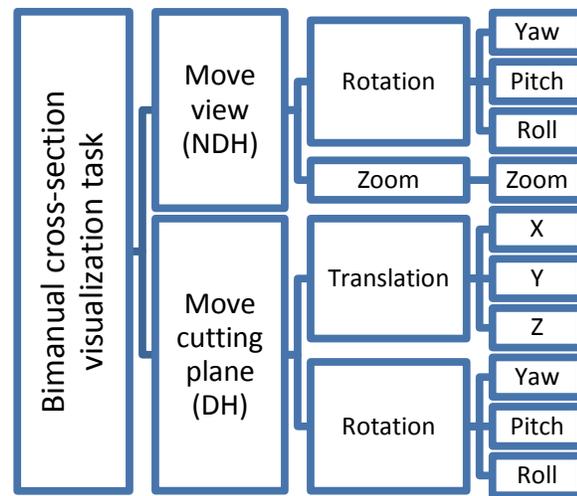


Fig. 3. Hierarchy of ten different subtasks making up a cross-section visualization task, that are integrated into a single bimanual task [4].

It was also shown that bimanual interaction can improve cognitive efficiency. Hinckley *et al.* performed an experiment in which participants had to align two virtual objects using either one or both hands, then try to reproduce the movement of the DH using only the haptic sense, without visual feedback [4]. The results showed that unimanual performance was improved if the bimanual condition was used before, which was not observed the other way around. This indicates that using both hands changed the subjects’ task-solving strategy at a cognitive level. Using two hands can also reduce the gap between novices and experts compared to the use of only one hand, as was shown with a navigation/selection task [32]. Owen *et al.* hypothesized that part of the performance gain could be explained by the fact bimanual interaction leaves more room for epistemic actions, *i.e.* motor actions performed in order to improve cognition, however the data obtained from their experiment was not fully conclusive [29].

2.4 Benefits of Bimanuality for Interaction

Most tasks operated naturally in real life can be naively thought as being unimanual, while they are in fact bimanual and often asymmetric [22]. An example of this is writing, where the NDH has a role of orienting the paper for the DH to write on it. Some experiments showed that the use of two hands remains natural in human-computer interaction [24], [32]. Thus, a first advantage of using two hands for haptic interaction is that it harnesses better our existing skills, that we use in everyday life.

Another benefit of bimanuality is that it increases task accuracy compared to the use of one hand through two-handed proprioceptive feedback, benefit which is more clearly visible when visual feedback is absent [3], [5]. Moreover, tasks can be achieved faster when two hands are used [29], [33], [34], [35]. This can be explained by the fact that two hands allow to realize tasks in less steps than with one hand, as illustrated with digital painting tasks, where several unimanual steps could be reduced to a single bimanual action [33], [36]. Also, two hands can be present at two separate points of action at the same time, which removes the time needed to switch positions between both, like for digital painting with the menus and workspace [34].

However, there can also be negative effects of using two hands on cognitive efficiency in some cases. Notably, when the tasks applied by the two hands are not sufficiently integrated, an effect of “division of attention” occurs between the two tasks and performance may decrease significantly [37]. Some known examples include the use of a mouse in each hand for independent tasks, which may lead to performances that do not exceed those of one-handed experiments [34], [38], [39]. For instance, the Toolglass metaphor [36], which integrates the selection of an operation and an operand by allowing users to click with their DH through buttons that are part of a see-through interface held by the NDH, performed better for digital painting than the use of two mice [38].

2.5 Discussion and Conclusion

A major element in bimanual haptic perception is our proprioception, which allows us to locate accurately both hands relatively to each other. Several studies have focused on the specialization of hands for haptic perception, and found increased proprioceptive sensitivity for the NDH [6], [7], transfer of trajectory information from the NDH to the DH, and transfer of endpoint limb position information from the DH to the NDH [18]. The integration of tasks between both hands appears to be a complex problem, as there are different possible integration schemes: visual [30], motor [31] and conceptual [4], [5].

The Kinematic Chain model implies a sequential and specialized role of both hands [22], and was

shown to be an efficient model for designing more natural and efficient bimanual interaction techniques [23], [24], [25], [26]. Furthermore, it was observed that tasks tend to be performed in a more asymmetric manner as they get more difficult [23], [27]. Two-handed interaction also allows better integration of different subtasks at a cognitive level, making seemingly complex tasks more simple [4], [29], [30], [31], [40]. However, this is only observed when the attention is not too divided, otherwise tasks may actually become more cognitively demanding [31], [34], [37], [38], [39].

The use of two hands is a common occurrence in our daily lives, that was shown to be applicable to the domain of human-computer interaction and more specifically haptics. Bimanuality brings a certain number of benefits, ranging from better accuracy [3], [5] to faster realization of tasks [29], [33], [34], [35]. Overall, taking into account these known elements about two-handed perception and action could greatly improve the efficiency of designed bimanual haptic hardware, software and interactive techniques.

3 BIMANUAL HAPTIC HARDWARE

In order to interact through both hands with a virtual or remote environment with haptic feedback, the first requirement is hardware that features both tracking of the position of two hands, possibly of the palms and fingers for more realistic interaction, and display of the computed feedback on these hands, being either kinesthetic, tactile, or both. Haptic hardware suited for bimanual interaction can be divided into two major categories. Single-point interfaces track the position and provide force feedback to a single effector for each hand. They can be grounded, *i.e.* their base is fixed, or mobile, in which case they are mounted on an element that can move around. Multi-finger interfaces track and provide kinesthetic or tactile feedback to multiple fingers per hand, and can be either grounded, or body-based, such as with haptic gloves for instance. This section focuses on these interfaces, by going through the aforementioned categories: single-point grounded, single-point mobile, multi-finger body-based and multi-finger grounded interfaces.

3.1 Single-Point Grounded Interfaces

Single-point interfaces have been widely used for bimanual interaction, notably due to their abundance. A notable example is the Phantom series of devices, which is a commercial model that is originally unimanual but used in a fair amount of bimanual haptic studies. There are also other devices that were more specifically designed for bimanual interaction.

3.1.1 Phantom devices

The Phantom family of devices from Geomagic (formerly Sensable) [41] has been used in several bimanual haptic studies. In all of these studies, these interfaces are underactuated, meaning that they have more DOFs in input (6DOF) than in output (3 translational DOF). However, 6DOF feedback versions of these devices do exist. The workspace includes various sizes depending on the model used, and can range from $16 \times 12 \times 7\text{cm}$ to $84 \times 58 \times 41\text{cm}$.

Dual Phantom devices were notably used in medical contexts, for instance with a simulator of ultrasound-guided needle puncture made with two PHANToM Omni devices [42], or a *da Vinci* Surgical System simulator developed with the same interfaces but improved with gripper devices [43]. Ullrich and Kuhlen used these devices as well, but replacing the stylus of one Omni device with a palpation pad, to simulate palpation interaction in a medical training simulator [44].

Another example is a 3D mesh manipulation software using two Phantom Desktop devices in conjunction with stereo vision [45]. Von der Heyde *et al.* also used two Phantom 3.0 interfaces to study one-handed grip tasks and two-handed pointing tasks [46] as well as part of a virtual laboratory for studying human behavior in complex tasks [47]. Finally, Kron *et al.* used Phantom devices for teleoperation, but using a Phantom Desktop device for the NDH, and a Phantom 1.5, which features a larger workspace, for the DH [48].

3.1.2 Other devices

Some commercial devices were designed with bimanual operation in mind, providing left-hand and right-hand versions of the interfaces. The omega.6 and omega.7 (Force Dimension) are underactuated devices, the latter providing active grasping capabilities, while the sigma.7 has 6DOF in both sensing and actuation and includes grasping as well [49]. The omega.7 notably showed its bimanual capabilities during an experiment involving two-armed surgical robot manipulation in microgravity [50]. The Freedom 6S and 7S devices (MPB Technologies) allow respectively 6DOF and 7DOF (with scissors handles) haptic interaction in a workspace fit to human forearms [51], [52]. Finally, the Virtuoso 6D from Haption [53] features 6DOF in both input and output, as well as a workspace fitting the movement of human arms. It was notably used for a virtual snap-in task between a deformable clip and quasi-rigid pipe [54], as well as for a virtual crepe preparation simulator, through the use of a virtual bowl in one hand and pan in the other hand for the manipulation of fluids [1] (Figure 1).

A bimanual haptic interface was developed by the German Aerospace Center (DLR) using two lightweight robot arms attached to the same column [55].

Each arm features 6DOF with an extra DOF that allows to avoid collisions between the two arms, the workspace provided by the combination of both being similar to that of human arms. The interface allows the use of different kinds of handles: a magnetic clutch that leaves the fingers free, a grip-force interface that allows the grasping of virtual objects, and a joystick handle that features a mini-joystick, a switch and buttons. Similarly, the VISHARD10 interface is a robot arm that features 6DOF in both input and output, with 4 extra DOF to avoid arm collision and increase the size of the workspace up to a cylindrical workspace of 1.7m of diameter and 0.6m of height [56]. Two VISHARD10 devices were used as a stationary human-system interface in a telepresence system [57].

The SPIDAR-G&G [58] consists of two SPIDAR-G devices [59], which are string-based unimanual devices with 6DOF for both motion and force feedback, and an additional DOF provided by a spherical element made of two hemispheres that a user can grasp to reproduce the same action in the virtual environment. The workspace of each interface is a cubic frame with 20cm of side length, and the two interfaces were separated by 40cm in the SPIDAR G&G prototype, thus avoiding interface collision issues.

The GRAB device [60] was built for either two-finger single-hand or one-finger two-handed interaction, with a focus on having a workspace large enough for two-handed manipulation with minimal encumbrance, while displaying forces representative of hand manipulation in unstructured environments. The fingertips fit into thimbles which serve as underactuated end effectors, with 6DOF sensing and 3DOF force display.

The bimanual surgical interface from Immersion Corp. [61] is a special case in that it is specifically designed for simulation of minimally invasive surgical procedures, and as such its design is close to that of the actual surgical tools with 5DOF for each manipulator.

3.2 Single-Point Mobile Interfaces

Mobile devices, by using the mobility of a robot carrying the haptic arms, can obtain almost infinite planar workspaces. An example is the Mobile Haptic Grasper [62], which is made of two grounded Phantom devices [41] mounted on a mobile robot. This device being limited to 3DOF in actuation, Peer and Buss used the VISHARD7 device [63], which features full 6DOF capabilities and is mountable on a mobile robot unlike the VISHARD10 [57], thus leading to a mobile bimanual interface similar to the MHG but with increased actuation. The latter also features a local workspace around the robot that fits the reach of human arms, allowing fast movements of higher amplitude than those permitted by the Phantom devices.

3.3 Multi-Finger Body-Based Interfaces

Multi-finger interfaces can take the form of gloves, that provide either kinesthetic or tactile feedback to the fingers while remaining entirely body-based. For kinesthetic feedback, two commercial devices from Immersion provide the necessary components for both sensing of all fingers the position of each phalanx of all fingers as well as the palm and wrist with the CyberGlove, and resistive force feedback to each of the fingers with the CyberGrasp, which are both available in left-hand and right-hand versions [64]. For tactile display, the CyberTouch is the vibrotactile counterpart of the CyberGrasp, to be used conjointly with the CyberGlove as well [64].

For tactile display, the GhostGlove is a glove that displays 2DoF tactile feedback on the palm and fingers through pulleys and motors [65]. Using a belt attached to dual motors, the device can display both vertical and shearing forces on each of the end effectors, however it is a pure display interface and as such does not provide sensing of the position and orientation of the palm and fingers by itself. The device was tested in a bimanual scenario of recognition of a virtual solid, leading to good recognition of the size of the object, though approximately 2 cm smaller for sizes varying between 19 and 28 cm [66].

The TactTip is a tactile module that can be attached to the fingertips with kinesthetic gloves such as the CyberGlove/CyberGrasp combination, providing both vibrotactile feedback and temperature feedback to all fingers [67]. While not tested in a bimanual context, it can be easily imagined that such modules could be used with two kinesthetic gloves at the same time. Hulin *et al.* noted a few tactile devices which could be used for bimanual interaction [68]. The A.R.T tactile finger feedback device uses optical tracking for finger position sensing and 3 wires around the fingertips that can contract and vibrate for tactile feedback [69], [70]. The DLR vibro-tactile feedback device provides tactile feedback to the entire forearm through two rings of vibration motors [71]. Finally, the DLR VibroTac also provides vibrotactile feedback to the arms using an array of vibration motors, and can be attached to either the upper arm, forearm or wrist [72].

3.4 Multi-Finger Grounded Interfaces

Similarly to single-point interaction, Phantom devices were also used for bimanual multi-fingered interaction. Barbagli *et al.* developed a system for two-handed two-fingered grasping of virtual objects by adding motors and sensors to Phantom devices [78]. A force reflecting gripper measures the relative position of the thumb and index, and gives force feedback when an object is grasped.

Two members of the SPIDAR family of string-based haptic display [79] were specifically designed for bi-

manual multi-fingered interaction. The first is Both-Hands SPIDAR [73] which is made of two SPIDAR-II devices [80] combined into the same frame, with non-overlapping workspaces. The SPIDAR-II allows to grasp virtual objects using the index and thumb of one hand, and as such the Both-Hands SPIDAR device bears the same capabilities with two hands. The other, more recent, SPIDAR system that provides the same kind of interaction is SPIDAR-8 [74] which is built on the same concept as Both-Hands SPIDAR but allowing interaction with four fingers per hand instead of two. Both systems have 3 degrees of freedom (DOF) in input and output for each finger.

The Bimanual HIRO system [75] was developed using two HIRO III devices [81], which are robotic arms similar to the DLR interface, with the difference that they are connected to all five fingertips of both hands of the user. The interface thus provides 3DOF in input and output for each of the fingertips, for a workspace covering the space of a desktop. The MasterFinger-2 was designed for two-fingered haptic interaction with the thumb and index, and its usability for two-handed manipulation was shown by using two of them jointly [76]. The MasterFinger-2 is underactuated, bearing 6DOF in sensing and 3DOF in actuation, with an additional DOF that helps increasing the workspace. The workspace for each finger is around 40 cm wide, but there should not be any interface collision if the bases are separated by more than 50 cm.

The Haptic Workstation from Immersion bears all the components necessary for a bimanual whole-hand haptic interaction [77]: additionally to the previously mentioned CyberGlove and CyberGrasp, the CyberForce provides 6DOF hand tracking and 3DOF force feedback on the wrists. The workspace is that of human arms when stretching them forward but slightly less on the sides, and is limited towards the torso, as well as subject to interface collision if the arms are crossed. The CyberGrasp was also combined with the DeKiFeD4, a robot arm-based haptic device that provides 4DOF of sensing and actuation (3 translation, 1 rotation), coupled with additional 6DOF force/torque sensors for the wrist, to provide a whole-hand interface for telepresence [48]. In a similar way, it was also noted that since the DLR bimanual haptic interface uses a magnetic clutch to couple the robot arm and the user's hand, it could be extensible to whole-hand interaction if combined with kinesthetic gloves [55] or tactile devices [68].

3.5 Discussion and Conclusion

A certain number of bimanual haptic interfaces exist, and they display a wide diversity in a lot of characteristics, as summarized in Table 1. The factor that has potentially the biggest impact is the number of degrees of freedom, which separates single-point interfaces from multi-fingered interfaces, with

TABLE 1
Overview of current bimanual haptic interfaces.

Device	Sensing	Actuation	End effector	Category	Mobility	Feedback
SPIDAR G&G [58]	6 + 1 DOF	6 + 1 DOF	Grip-force interface	Single-point	Grounded	Kinesthetic
omega.6 [49]	6 DOF	3 DOF	Stylus			
omega.7 [49]	6 + 1 DOF	3 + 1 DOF	Grip-force interface			
sigma.7 [49]	6 + 1 DOF	6 + 1 DOF	Grip-force interface			
Freedom 6S [52]	6 DOF	6 DOF	Stylus			
Freedom 7S [51]	6 + 1 DOF	6 + 1 DOF	Scissors grip			
DLR BHD [55]	6 (+ 1) DOF	6 (+ 1) DOF	Variable			
Geomagic Touch [41]	6 DOF	3-6 DOF	Stylus			
GRAB [60]	6 DOF	3 DOF	Thimble			
Virtuose 6D [53]	6 DOF	6 DOF	Handle			
VISHARD10 [56]	6 DOF	6 DOF	Handle			
MHG [62]	6 DOF	3 DOF	Stylus		Mobile	
Mobile VISHARD7 [63]	6 DOF	6 DOF	Handle			
Both-Hands SPIDAR [73]	3 × 2 DOF	3 × 2 DOF	2 fingertips	Multi-finger	Grounded	
SPIDAR-8 [74]	3 × 4 DOF	3 × 4 DOF	4 fingertips			
Bimanual HIRO [75]	3 × 5 DOF	3 × 5 DOF	5 fingertips			
MasterFinger-2 [76]	6 × 2 DOF	3 × 2 DOF	2 fingertips			
Haptic Workstation [77]	6 + 22 DOF	3 + 5 DOF	Whole hand + wrist			
CyberGlove/Grasp [64]	22 DOF	5 DOF	Whole hand		Body-based	
GhostGlove [65]	N/A	2 + 2 × 5 DOF	Palm + 5 fingertips			Tactile
CyberTouch [64]	18-22 DOF	0-125 Hz	Palm + 5 fingers			

the special case of whole-hand interfaces for the latter. However, even within each category there is a certain range of degrees of freedom. For example, while some single-point kinesthetic interfaces are underactuated with 6DOF in sensing and 3DOF in actuation, others can have 6DOF for both and potentially an extra DOF for grasping. For multi-finger interfaces, most of them are 3DOF devices while the variety lies in the number of fingers supported, though the MasterFinger-2 [76] chose to trade the number of fingers for more DOF in sensing. Some of these multi-fingered interfaces also include the palm, increasing even further the number of DOF. Tactile devices have an even wider range of possible outputs, whether through motors with belts/wires pulling fingertips in one or more directions, thermoelectric elements for heat display on the fingertips, or vibrating motors for either the fingers or the arm. The great differences between all of these categories raise different problematics in terms of haptic rendering, which will be covered in the next section.

There is also a wide range of workspace sizes. Some devices have a small workspace, like the Phantom, while others offer a workspace adapted to movements of the forearm (e.g. Freedom 6S [52]) or the entire arm (e.g. Haptic Workstation [77]). Finally, some of them allow to move in an almost infinite horizontal space through mobile robots. An additional issue concerning workspaces is that of interface collision. Some devices with small workspaces, like the SPIDAR G&G [58], are distant enough from each other to avoid such

problems. Most interfaces with bigger workspaces, however, do encounter this issue, although some of them incorporate additional DOFs to avoid it, like the DLR bimanual haptic device. Great variability is also observed in terms of exertable forces, as the maximum peak forces can range from as low as 2.5N for the Freedom 6S [52], for instance, up to 154 N for the VISHARD7 [63].

This large spectrum of possibilities for all of these haptic devices makes it all the more difficult to develop generic software solutions that would encompass all of them. For instance, for mobile devices, a controller for the mobile robot has to be added. Grounded devices have workspace limits that require interaction techniques to overcome them. A whole-hand interface needs virtual hand models to handle the repartition of forces over the phalanges, palm and wrist. Tactile devices, whether they are based on vibrations, temperature or motors, may also require different kinds of controllers.

Another element worth noting is that most presented interfaces are symmetrical: not taking into account the adaptation to the left and right hands for some of them, in most cases the same device is used in each hand. The case where each hand holds a different interface has scarcely been investigated, apart from a few cases like the study of de Pascale *et al.* [82] on grasping of locally deformable objects with two different PHANToM devices. Kron *et al.* pushed the concept further in teleoperation by providing two different grippers to the telemanipulator

[48], while the work by Ullrich and Kuhlen assigned two different tasks in a virtual environment, with an adapted PHANToM Omni for palpation with the non-dominant hand. Talvas *et al.* opened the way for further studies on bimanual interaction with asymmetric interfaces, by using a PHANToM Omni and a Novint Falcon to propose new interaction techniques for navigation and manipulation in virtual environments [83]. Considering the specificities of the NDH and DH as well as their interconnections described in section 2, it would potentially be beneficial to use different devices for both hands more often by taking into account their respective roles.

4 BIMANUAL HAPTIC SOFTWARE

Following the overview of the available two-handed haptic hardware, this section focuses on the software side of bimanual haptic interaction. The physically-based methods used to simulate haptic virtual environments are first developed, then the haptic rendering techniques that allow the user to interact with such environments and receive force feedback from it. Existing haptic Application Programming Interfaces (APIs), as well as software developed using these APIs, are overviewed, before briefly discussing the architectures of the latter.

4.1 Physical Simulation

In virtual reality, the interaction between different objects of a virtual environment can be handled in a realistic way by physical simulation. To this date, the methods used for physical simulation in bimanual haptics are exactly the same as the ones used in unimanual context. The most classic kind is the simulation of rigid bodies, which involves collision detection between bodies, and collision response to prevent interpenetration of colliding bodies. Most commonly known physics engines, such as Open Dynamics Engine [84], Bullet Physics [85], PhysX [86] or Havok Physics [87], handle rigid body dynamics.

For deformable bodies, Duriez *et al.* remarked that both haptic output from real-time deformation algorithms and friction models were mostly simplified, and subsequently studied the haptic manipulation of several deformable objects with contact constraints and friction [54]. They also proposed a corotational approach to decouple rigid global motion from local deformation, allowing to maintain haptic frame rates even with deformable body simulation based on the computationally expensive finite element method (FEM). This model was tested on a bimanual haptic simulation, with a snap-in task between a deformable clip and a rigid or deformable pipe.

A method for haptic and graphic simulation of quasi-rigid bodies has been proposed, but the deformations are only computed locally around a contact point [88]. Ott explored bimanual haptic manipulation

of soft bodies using PhysX, which supports fabrics, however while the physical simulation was correctly performed, haptic rendering was not possible due to the PhysX library keeping internal the collision detection results with soft bodies [89].

The medical simulation framework SOFA [90] implements a few deformable models such as FEM, and was used in bimanual haptics for a medical training simulator [91] as well as for an immersive ultrasound-guided needle puncture simulator [92]. Finally, concerning fluid simulation, a method has been recently proposed for simulation of both rigid bodies and fluids through smoothed-particle hydrodynamics (SPH), shown to be suitable for bimanual haptics [1].

4.2 Force Display

Similarly to physical simulation, techniques used in two-handed haptics for transmitting forces from either a remote or virtual environment to the user are similar to those used in unimanual haptics. For instance, in telepresence, the position of the hands of the operator are sent to the telemanipulator, and the interaction forces sensed by both arms of the latter are fed back to both haptic devices, with filtering of the received forces in order not to exceed the maximum capabilities of the devices [48], [99]. In virtual reality, common unimanual techniques such as virtual proxies are usually used, though there are some techniques that are specific to the bimanual case, which revolve mostly around grasping.

For haptic rendering with virtual environments, a commonly used technique is the god-object method [100], which uses a representation of the haptic device in the simulation that will respond to physical constraints. Virtual coupling [101] is used to stabilize the simulation by applying a spring-damper link between the haptic device and its virtual counterpart. The use of virtual proxies, *i.e.* representations of the haptic objects with an object instead of a point, was later proposed along with smoothing of object surfaces and the addition of friction [102]. These techniques were however limited to 3DOF interaction, thus a generalization to 6DOF interaction with rigid bodies was proposed, notably performing well with objects of high complexity [103].

A special case of the use of this god-object method in bimanual haptics is that of virtual hands, such as the mass-spring hand model developed by Ott for the Haptic Workstation [89], in which the palm and each phalanx are represented by rigid bodies, linked by joints with springs and damping. The spring-hand model has a soft constraint which makes it follow the movements of the tracked hand, while still being physically constrained by collision with other elements of the virtual environment. It thus notably allows to know where force feedback should be distributed between the palm and the fingers.

TABLE 2
APIs usable for bimanual haptic interaction.

API	Category	Supported devices	Capabilities (aside device control)
Haptic SDK [93]	Device-specific	Force Dimension	
OpenHaptics [41]		Geomagic	Haptic rendering
Freedom 6S API		MPB Technologies	
HDAL SDK [94]		Novint	
libnifalcon [95]		Novint	
MHaptic [89]		Haptic Workstation	Haptic rendering, physics, graphics
JTouchToolkit		Geomagic, Novint	Graphics
HAPI	Generic	Geomagic, Novint, Moog FCS Robotics, Force Dimension	Haptic rendering
Haptik Library [96]		Geomagic, Haption, Force Dimension, MPB Technologies, Novint	Networking
CHAI 3D [97]		Force Dimension, Novint, MPB Technologies, Geomagic	Haptic rendering, graphics
H3DAPI [98]		Geomagic, Force Dimension, Novint, Moog FCS Robotics	Haptic rendering, graphics

Additionally, a generalized god-object method was proposed to simulate realistically the behaviour of virtual hands by preventing the penetration of objects, generating plausible finger postures, and avoiding other artifacts like artificial friction or phalanxes being stuck inside objects [104]. A possible improvement for those virtual hands is the use of deformable soft bodies for each phalanx, which simulate the adaptation of the finger to the shape of manipulated objects [105]. It thus ensures firmer handling of virtual objects with increased contact area and thus increased friction.

Haptic rendering in the specific case of bimanual haptics has revolved a lot around the rendering of grasping of virtual objects. An early method proposed, for a 1DOF grasping situation, to compute the impedance by taking into account both contact points into the same calculation, and calculating separately the external forces (which have an effect on the motion of the grasped object) and the internal forces (which are unrelated to that motion), with different stiffness and damping coefficients for each [106].

Barbagli *et al.* defined the minimal requirements for simulating grasping of an object [78]: either 7 frictionless point contacts, 3 point contacts with friction, or 2 “soft-finger” contacts. Soft fingers are defined here as proxies that emulate human fingers, bearing sufficient torsional friction around the contact normals, and a method was proposed to fully restrain virtual objects with two 4DOF devices based on that principle [107].

Finally, a more recent study focused on multi-finger grasping of virtual objects, and two solutions were proposed [76]. The first solution consists in separating objects in two halves and connecting those halves by springs. This solution works well if the object is to be grasped from opposite points, but not when it is grasped from neighbor points. The second solution proposes to simulate springs between all fingers that manipulate an object, and have the force feedback be

that of the spring and no longer that of the collision response with the object.

4.3 Haptic APIs

Several APIs are available to handle haptics in applications, however they tend not to explicitly show if they support multiple devices at the same time, which may confuse a developer interested in bimanual haptics. This section focuses on these APIs, and a summary of most existing APIs is shown on Table 2, all of which being able to handle multiple devices.

Haptic APIs can be divided in two major categories: device-specific and generic APIs. Device-specific APIs provide low-level access to one device or series of devices. Most of them are developed for unimanual devices, but MHaptic in particular is bimanual-oriented, the Haptic Workstation being a two-handed device [89]. Generic libraries have the advantage over device-specific APIs of supporting different haptic devices.

A few of these APIs have been used as a framework to develop bimanual haptic software. An example is the M4 system for visuo-haptic manipulation of 3D meshes [45], for which the software layer was developed on top of H3DAPI. Some H3D nodes were extended to provide grabbing ability for the non-dominant hand and mesh manipulation abilities (cutting, deforming and painting) for the dominant hand, although two handed manipulation of the mesh is also made possible.

The Haptik Library was also used to develop the software layer of the Mobile Haptic Grasper [62]. A plugin was specifically designed to control the mobile part of the system and added to the library, allowing any user to use mobile interfaces with the simple principle that a mobile device can be considered a grounded device with a huge workspace. Grasping

was included in the software using the previously mentioned soft fingers method.

4.4 Architectures

The software architectures for bimanual haptics differ whether we look at the cases of telepresence, or virtual reality, due to the different requirements of both contexts. While both share haptic control threads, on one side the teleoperation case has to deal with networking and teleoperator arm configurations, and on the other side the virtual reality case has to deal with collision detection and simulation. In both cases, however, the architectures tend not to be very different from those used for unimanual haptics.

Bimanual haptic teleoperation follows the same software structure as for unimanual telepresence, that is to say a haptic control loop communicating with the haptic devices, a teleoperator control loop which communicates with the manipulator arms, and data sent through UDP communication between the two [48], [99]. It can optionally include collision avoidance algorithms to detect dangerous configurations of the manipulator arms and provide force feedback to avoid those [48].

Architectures used in bimanual interaction with virtual environments are rarely explicated, however three papers described those architectures in a comprehensive way, by Ott for the MHaptic library [77], Garcia-Robledo *et al.* for the presentation of the MasterFinger-2 used in a bimanual context [108], and Ullrich *et al.* for the Bimanual Haptic Simulator [91].

The two first architectures bear certain similarities, notably the fact they follow the same scheme: a simulation thread, two haptic threads, and a visual rendering thread. The simulation thread manages the virtual environment by detecting collisions and then solving object-object and device-object collisions. This thread includes a haptic hand model in the case of MHaptic while the MasterFinger-2 includes a grasping detector. The haptic threads read raw positions and orientations from the sensors and manage the actuators according to the results of the simulation, the special case of MHaptic integrating an anti-gravity software to improve user comfort in these threads. The visual rendering thread simply reads the data from the simulation (and the hand model in the case of MHaptic) and displays it to the user.

The architecture of the Bimanual Haptic Simulator is fairly similar to the two others but with clear differences as well, aside the fact it simulates deformable bodies. The similar parts are the presence of the simulation and visual rendering threads, though their refresh rates are drastically different from the previous ones. Notably, the physics thread runs at 25 Hz instead of 200-300 Hz due to the computationally intensive nature of deformable body simulation. Also, while the previous systems had a single thread for each haptic device, this one has two

threads per device: an interaction thread and a force algorithms/haptic rendering thread. While the latter could be considered similar to the haptic threads of the previous systems, running at 1 kHz and taking care of force feedback (with special force effects), the former is completely different, handling haptic device/simulated tissue interactions, which was a part that was present in the single simulation thread in the other architectures.

4.5 Discussion and Conclusion

Physical simulation techniques for bimanual haptics are mostly the same as those used for unimanual haptics, most often geometry-based rigid body simulation. However, other kinds of simulation have been explored, such as locally deformable bodies, mass-spring-based deformable bodies, and multi-state particle-based systems.

Bimanual haptic rendering is similar to the unimanual case as well, with notably universal techniques like the god-object and proxy methods. Actual bimanual techniques have also been developed, focusing mostly on the rendering of grasping with single-point or multi-finger interfaces. However, very much like bimanual hardware, those techniques consider the two hands equally, not taking into account any form of asymmetry of the hands.

These bimanual rendering methods are not really implemented in existing haptic APIs. Some of these APIs offer support of multiple point-based devices, but none of them show truly bimanual functionalities. An exception is the special case of MHaptic, which is entirely focused on the whole-hand bimanual interface Haptic Workstation. A point worth noting is that generic APIs were shown as suitable for developing bimanual software, as illustrated by the cases of H3D-API and Haptic Library.

Bimanual haptic software follows a multithreaded architecture with common visual rendering and physical simulation threads, though the handling of haptic devices may differ slightly between architectures. While haptic rendering is always performed in a separate thread for each device at a high rate, interactions between haptic devices and the objects of the simulation can be handled either in the common simulation thread, or in one specific thread for each device. The chosen refresh rates are also quite variable, notably with different trade-offs between a more frequently updated physical simulation and smoother visual rendering.

5 INTERACTION TECHNIQUES

The previous sections dealt with three separate elements of bimanual haptic interaction: user, hardware and software. Interaction techniques gather all of these elements, combining hardware and software solutions to allow a user to perform a specific task.

TABLE 3
Thread refresh rates for three bimanual haptic software architectures.

Software	Simulation	Haptic	Interaction	Physics	Visual
MHaptic [89]	Rigid body	950 Hz	N/A	300 Hz	60 Hz
MasterFinger-2 [108]	Rigid body	1,000 Hz	N/A	200 Hz	50 Hz
Bimanual Haptic Simulator [91]	Deformable	1,000 Hz	120 Hz	25 Hz	Unlimited

There are very few interaction techniques that can be considered purely bimanual haptic, and are mostly related to virtual reality. However, this list can be enriched by looking at close fields such as unimanual haptic interaction, which techniques can be used in a dual way for bimanual haptics. Non-haptic two-handed interaction techniques also bear principles that could be used as inspirations for new bimanual haptic techniques.

An element of classification for 3D interaction techniques is the taxonomy of Bowman [109], which defines four main classes of interaction: navigation, selection, manipulation and system control. The interaction techniques that are reviewed in this section unevenly fit these categories, hence these techniques will be reviewed following two categories. Firstly, we consider the parts of the interaction that do not involve direct interaction with virtual objects, encompassing navigation and system control. Then, we consider the interaction with virtual objects, including selection and manipulation.

5.1 Navigation and System Control

As far as navigation and system control techniques are concerned, genuinely bimanual haptic techniques are close to nonexistent. Such techniques are rather found in the more general field of two-handed 3D interaction, though one of the techniques that will be discussed here is originated from the unimanual haptics field and was adapted to bimanual haptics.

An early technique in the field of 3D graphics interfaces proposed to use the non-dominant hand for controlling the camera while the dominant hand executes the tasks [110]. While such technique could be hardly used in conjunction with tasks requiring both hands in a virtual environment, a scenario could be considered where only one hand is performing a task while navigation is required at the same time (like moving a light object over a long distance), secondary task which could be assigned to the other hand. The *bulldozer* metaphor was also proposed, for navigation in 3D environments with 2D interfaces [111]. Using a dual joystick configuration, the user is given 4DOF navigation capabilities (3DOF in translation and rotation around the y axis), using a metaphor similar to the handling of a shopping cart: pushing both joysticks forward for moving forward, pulling them both to move backwards, pushing both on the same side to move sideways and pulling one while

pushing the other to turn. Translation on the y axis was added by having the user push both joysticks on opposite sides. That interaction technique being close to a real life task, it was shown to perform well, and could potentially be adapted for 3D interfaces.

The *bubble* technique is a unimanual haptic navigation technique that defines a sphere in which the haptic devices will control the proxy in position, while leaving the sphere boundaries will switch into a rate control, with an elastic radial force sent back to the user [112]. This technique has been adapted in a bimanual context by Ott for the Haptic Workstation, in which case having both arms reaching the workspace limits would either move the camera forward or rotate it [89]. Another implementation was more recently proposed, called *double bubble*, which provides a *bubble* to each hand instead of a common one for both [83] (Figure 4). These *bubbles* can move independently from each other, except when both proxies manipulate the same object, in which case both *bubbles* are adjusted to the same size and velocity, allowing easier navigation within the virtual environment while holding a virtual object with both hands. The *double bubble* was compared to the *clutching* technique, which consists in a decoupling between device and proxy when the user presses a button on the interface, and was shown to perform better in terms of speed, accuracy and user appreciation.

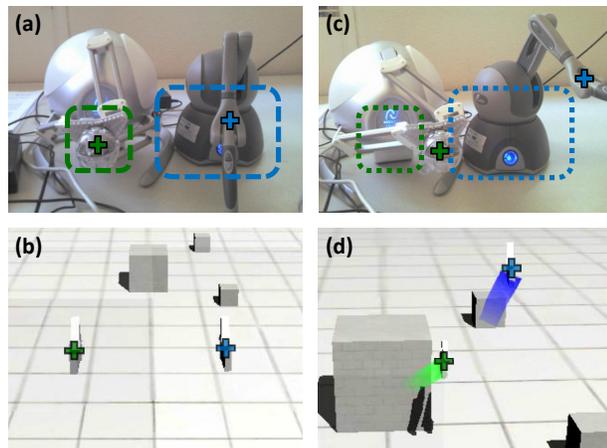


Fig. 4. Control modes of the *double bubble* technique. (a-b) Devices inside the *bubbles* : position control. (c-d) Devices outside the *bubbles* : rate control. [83]

Finally, an alternate and generic way to facilitate

navigation in virtual environments is to increase the number of degrees of freedom available to the user. Such interaction technique that allows navigation while having both hands occupied simultaneously by tasks was proposed in a context of teleoperation, by using a 3DOF foot pedal for moving the controlled robot [99]. More recently, two foot pedals were also integrated into the DLR bimanual haptic device, which could be assigned to different tasks [68].

As far as system control techniques are concerned, in the context of 3D interaction techniques, Cutler *et al.* proposed ways to apply transitions between different tools, or subtasks, proposed to the user with the Responsive Workbench [24]. They defined explicit transitions, like picking up a tool in a toolbox, with a default behaviour when no tool has been picked up yet, that should be specific of the application. Another example of explicit transition, more practical in that it does not require several movements between the workspace and the toolbox, is the use of hand gestures. Implicit transitions were also defined, in which switching from a subtask to another happens seamlessly, almost imperceptibly. An example of this is the switch from a unimanual grabbing technique to a bimanual grab-and-twirl technique, that occurs naturally as the user reaches in with the other hand to help the manipulation.

5.2 Selection and Manipulation

In the case of physically-based virtual environments, the act of “selecting” an object with haptic devices is implicit. Touching an object with the representation of a haptic device in the simulation, such as the previously mentioned god-objects [100], [102], [103], will lead to the generation of one or more contact points by the collision detection engine. Doing so with a second virtual proxy simply adds more contact points to the simulation, which are then resolved in the same manner.

Specifically two-handed haptic techniques were proposed to detect when a user attempts to grasp an object [83], [108]. In the case of multi-fingered interfaces, a study on the segmentation of a grasping task allowed to distinguish 3 major steps with specific forces applied on the grasped object: approach (no force applied on the object), gripping (a horizontal force being applied), and lifting (a vertical component being added) [108]. The information on the forces applied by each finger on an object can thus allow the controller to detect grasping and simulate it accordingly. For dual single-point haptic interfaces, it was proposed that grasping can be defined as the application of two sufficiently strong contact forces with proxies that are facing each other [83]. This latter point is determined by casting rays from each proxy along the contact normals, and checking if each ray hits the other proxy. These rays can be cylinders of a

certain radius, the radius setting the tolerance of the detection.

For haptic manipulation of virtual objects, current interaction techniques mostly consist in the use of a unimanual technique in a dual way, or with an adaptation for two-handed interaction. This can be seen with the example of virtual hands, the same model being used for both hands, symmetry aside. Same can be said of *god-object* methods, which represent either the hand or fingers with single points that all bear the same characteristics. Virtual proxy methods, however, allow to assign two different tools to each hand. This is the case of the M4 system [45] in which, for instance, a hand can deform a mesh while the other is painting on it. The use of passive interfaces, or “props”, can also allow to assign different tasks to each hand ; for instance Lindeman *et al.* [113] proposed hand-held windows on the non-dominant hand on which the dominant hand could act.

The two-handed grasping of virtual objects with single-point interfaces can be a challenging task. Thus, a method was proposed to simplify such tasks, by simulating springs between virtual proxies and picked object (Figure 5), giving a feel of the user’s hands being “magnetized” to the object [83]. For a task involving the picking of a virtual object and carrying to a marked target, this led to significantly faster completion times, reduced number of unwanted drops of the object, as well as better overall user appreciation.

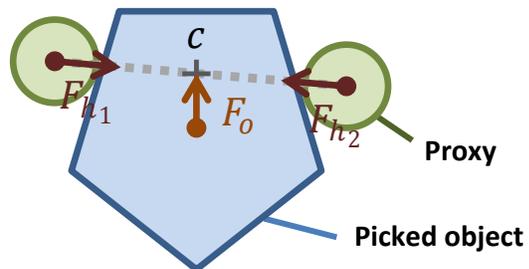


Fig. 5. Sticking of a virtual object to two single-point haptic interfaces with the *magnetic pinch*. F_{h_1} and F_{h_2} are the forces applied on the centers of mass of both proxies to pull them towards each other. F_o is the force applied on the center of mass of the picked object to pull it towards c , the middle point between both virtual proxies. [83]

Another technique proposed to improve the manipulation of virtual objects is the *god-finger* method, which proved suitable for improving the bimanual grasping of virtual objects as well [114]. The method computes a contact area from the information of a single contact point without resorting to deformable body simulation, hence constraining better the rotations of objects, notably around the grasping axis (Figure 6).

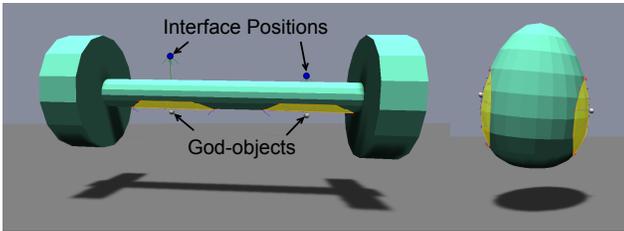


Fig. 6. Lifting of virtual objects with two proxies using the *god-finger* technique. The contact areas are highlighted.

5.3 Discussion and Conclusion

Interaction techniques can be used to enhance the bimanual haptic interaction of a user with a virtual environment, by combining hardware and software solutions to produce efficient metaphors. The amount of two-handed haptic interaction techniques remains fairly limited to this date, but some pioneering works are starting to emerge.

As far as navigation techniques are concerned, a couple of methods worth noting are adaptations of the *bubble* technique [112]. The MHaptic implementation barely exploited the bimanual capabilities, simply requiring to push both hands in the same direction instead of only one [89]. The *double bubble* [83] allows to move hands both independently from each other in free space and conjointly when manipulating, also permitting the use of different hardware in each hand. These techniques could be improved by taking from metaphors like the *bulldozer* metaphor, which originally allowed more DOFs for navigation in the virtual environment using less DOFs in input. The asymmetry of the hands could also be taken into account by, for instance, only assigning navigation tasks to one hand, leaving the other hand free for other tasks. The use of foot pedals for navigating seems to be one of the most natural options, as we use usually our feet to navigate, however it is only possible with the appropriate hardware. There is also a clear lack of system control techniques for bimanual haptic interaction. So far, there is only pioneering work available for transitioning between tools, both unimanual and bimanual, in the more general context of 3D interaction [24], but the adaptation of these transitions to the bimanual haptic context remains to be done.

Selection and manipulation techniques are currently not much different from the unimanual haptics field: god-objects, proxies or hand models being often simply duplicated and thus giving the same interaction possibilities to both hands and not taking into account the possibilities given by the combination of both. Still, bimanual haptic methods are starting to emerge, notably with methods to detect the user's intent of grasping an object, either through the study of the different steps of grasping [108], or using the

information of contact forces and normals [83]. These selection methods can be used to trigger manipulation techniques, which in turn may simplify the manipulation of the grasped object, such as with the use of virtual springs to stick the grasped object to the virtual proxies [83]. Manipulation techniques can also stabilize the interaction between proxies and object, for instance by simulating contact areas [114].

6 CONCLUSION

6.1 Summary

Haptics can greatly enhance the immersion of a user into a simulated or remote environment by stimulating the tactile and proprioceptive senses. Therefore, it has many applications in several fields such as medicine or industry. However, while haptics through the use of a single device has been widely investigated, the same cannot be said of haptics that use both hands. Several studies highlighted that the use of two hands is a common happening in our daily lives, sometimes without even noticing it. It was shown that there are clear benefits of using two hands, both in general and more specifically in human-computer interaction, which are related to the speed, accuracy and mental schemes with which tasks are carried out.

The cognitive aspects of bimanual interaction have been well studied, notably with Guiard's Kinematic Chain model serving as a solid basis [22]. It defines three major principles concerning the relationship between the dominant hand and the non-dominant hand, more precisely that the latter precedes the former in action, serves as a frame of reference, and acts at a bigger spatio-temporal scale. Other cognitive facts in the use of two-handed were observed, notably the fact it helps compiling different subtasks into single, less cognitively heavy tasks, and also that the level of asymmetry deployed to do a task is directly correlated to the difficulty of that task. This whole state of knowledge on bimanual interaction needs to be taken into account when developing bimanual haptic hardware, software and interaction techniques, as failing to do so may lead to a huge loss of the benefits of this form of interaction.

Several bimanual haptic devices have been created, whether mechanically designed to be bimanual or being unimanual devices adapted for two-handed use, although it was shown that unadapted unimanual devices could be used for bimanual interaction as well. All of these devices show a great variety in terms of degrees of freedom in both sensing and actuation, including the possible use of multiple fingers or the wrist, but also a variety of workspace sizes, continuous and maximum peak forces, etc. Most of these interfaces, however, are kinesthetic, with only a couple of devices shown to be suitable for bimanual tactile feedback. Also, all of them are symmetrical, the same device being used in each hand.

As far as the bimanual haptic software is concerned, to this day little has been done to develop techniques that differ truly from those used in unimanual haptics. Physical simulation techniques are similar, some recent studies having opened the way for simulation of fluids and multi-state bodies, all compatible with bimanual interaction [1]. Haptic rendering is similar as well, though more specific techniques for haptic rendering of grasping exist for both single-point and multi-finger interfaces. A point of note here is that, same as for hardware, haptic rendering techniques are also symmetrical, considering both hands equally. Current haptic APIs support the use of two interfaces conjointly, but still lack true bimanual capabilities. However, some of them were shown to be suitable to develop bimanual software. Bimanual haptic software usually follows a dual control loop scheme for telepresence, and a multithreaded architecture for virtual reality with a simulation thread, a visual rendering thread, and dual haptic threads.

There is finally a lack of bimanual haptic interaction techniques, the few ones being the bimanual adaptation of the *bubble* technique for navigation in virtual environments, the use of different proxies in each hand assigned to different manipulation tasks, and the detection of grasping through the forces applied to an object. Some generic techniques can be applied to bimanual haptics, though, like the use of foot pedals to allow navigation without monopolizing the hands.

6.2 Applications of bimanual haptics

Bimanual haptics has already found its place in a few fields of application, a notable example being that of the medical field. In this context, surgery training has been a good application of two-handed haptics, as it allows surgeons to train without putting the patients' health in danger, but also reducing training costs. A bimanual surgical simulator interface for simulation of minimally invasive surgical procedures [61] was shown to improve the efficiency of training of surgeons, reducing error rates [115]. Similarly, a *da Vinci* Surgical System Simulator was developed for simulation of the *da Vinci* system for robot-assisted minimally invasive surgery, which usually requires extended learning times [43].

Two-handed haptics is however not only useful for training surgeons, another important medical field being that of bimanual training in rehabilitation, which encompasses a number of methods for helping the recovery of a paretic arm through the joint use of both arms [116]. An example of this is the use of a bimanual haptic desktop platform for upper-limb post-stroke rehabilitation, simultaneously proposing exercises for the rehabilitation and methods of assessment of the patient's progress [117]. Robotic bimanual arm trainers [118], [119], [120] were also successfully used as alternatives to classical rehabilitation methods

for hemiparetic subjects after stroke. Rehabilitation of a paretic hand was also made possible through a robotic hand exoskeleton, by using data acquired from the grasping of an object by the healthy hand to adjust the force applied by the affected hand when performing the same grasp [121].

The current applications of two-handed haptics are not limited to medicine, though, and other applications in virtual reality include industrial prototyping, as illustrated by an assembly test of a coolant tank inside a car engine hood [55], showing the possibility of detecting design errors using only virtual models, even at early design stages. Another application is 3D modeling, as demonstrated with the M4 system for cutting, deformation and painting of 3D meshes [45]. This software additionally displayed ways to use the asymmetry of the hands, by either having the non-dominant hand modify the orientation of the object the other hand works on, or by using another tool at the same time. In telepresence, a shown possible application of bimanual haptics was remote demining operations, for which a bimanual manipulator is necessary for two-handed operations such as unscrewing [48].

6.3 Perspectives

An important point for the future of bimanual haptics will be to use the current state of knowledge on the cognitive aspects of two-hand use as a starting point for designing hardware, software and interaction techniques. It was stated earlier that all bimanual hardware was symmetrical, and yet it is known that both hands work at different scales, so this fact could potentially be used to think of asymmetrical interfaces. A possibility would be having an interface with a bigger workspace or stronger force feedback for the non-dominant hand, or a better resolution for the dominant hand. Same could be said of haptic rendering techniques: using different scaling, stiffness or damping factors on each hand to account for their inherent asymmetry. Another point worth studying is that of refresh rates: whether having equal rates is truly necessary for updating both devices, or if it would be possible to have one device updated less often. Finally, since we know that the non-dominant hand leads the action and that the dominant hand uses it as a frame of reference, interaction techniques could be developed to fully exploit the capabilities of both hands.

Another perspective in terms of hardware will be to integrate both tactile and kinesthetic feedback in two-handed haptics, as they are for the time being well separated. Some tools are already there to do so, for instance robotic arms that can track the arm without restricting the fingers, coupled to a tactile interface that can stimulate the fingertips. There is still room for a lot more work on the subject, as these two classes of

interfaces tend to spatially exclude each other, notably at the fingertips.

As far as software is concerned, the current physical simulation and haptic rendering methods do not consider the bimanual case as different from the unimanual case. However, especially in the multi-finger case, using two hands increases the number of contacts and may lead to a high computational cost or stability problems when it comes to physical simulation, which is a matter worth studying. Also, integrating true bimanual functionalities such as grasping haptic rendering techniques to the current APIs would be a step forward for helping the development of bimanual haptic software.

Concerning interaction techniques, there is still much to be done to provide a comprehensive set of bimanual haptic techniques. A few navigation techniques have been proposed so far, each with their set of advantages and drawbacks, and it still remains difficult to move two-handedly within a virtual environment with complete freedom without requiring very specific hardware. Manipulation techniques could also be improved to better take into account the specificities of each hand. Finally, until now, most bimanual haptic studies implied having only one function assigned to each hand, so there is still a lot to explore on how to allow users to switch between different tasks in a way that would be as seamless as possible, so as to extend the field of actions they can do in a virtual environment.

On the long term, a goal worth aiming for is a seamless haptic interaction with a virtual environment using both whole hands, providing convincing feedback during the manipulation of virtual objects, in a manner as natural as in real life, allowing a wide range of tasks. This will require contributions from all of the aforementioned fields, for which the works that have been reviewed in this paper provide solid foundations.

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