DesktopGlove: a Multi-finger Force Feedback Interface
Separating Degrees of Freedom Between Hands

Merwan Achibet†
Inria/INSA Rennes
Géry Casiez‡
Université de Lille
Maud Marchal†
Inria/INSA Rennes

Abstract
In virtual environments, interacting directly with our hands and fingers greatly contributes to immersion, especially when force feedback is provided for simulating the touch of virtual objects. Yet, common haptic interfaces are unfit for multi-finger manipulation and only costly and cumbersome grounded exoskeletons do provide all the efforts expected from object manipulation. To make multi-finger haptic interaction more accessible, we propose to combine two affordable haptic interfaces into a bimanual setup named DesktopGlove. With this approach, each hand is in charge of different components of object manipulation: one commands the global motion of a virtual hand while the other controls its fingers for grasping. In addition, each hand is subjected to forces that relate to its own degrees of freedom so that users perceive a variety of haptic effects through both of them. Our results show that (1) users are able to integrate the separated degrees of freedom of DesktopGlove to efficiently control a virtual hand in a posing task, (2) DesktopGlove shows overall better performance than a traditional data glove and is preferred by users, and (3) users considered the separated haptic feedback realistic and accurate for manipulating objects in virtual environments.

Index Terms: H.5.2 [Information Interfaces and Presentation]: User Interfaces—Haptic I/O

1 Introduction
Directly using our hands to explore virtual environments produces a natural and compelling interaction. However, it requires complex multi-finger interfaces with the dual purpose of (1) tracking the user’s hand to drive its virtual representation and (2) delivering force feedback to simulate the touch of virtual objects.

Multi-finger input has traditionally been tackled with motion capture, a powerful approach that transposes the user’s gestures into the virtual world [36, 35]. Recent research generalized this technology by leveraging off-the-shelf cameras [40, 33] and low-cost sensors [23, 1], increasing its accessibility and attractiveness furthermore. Even so, the lack of haptic feedback of those “in-the-air” interfaces makes for a shallow user experience, akin to interacting in a ghostly world whose contents lack tangibility.

Consequently, haptic interfaces that stimulate the sense of touch are needed to appreciate the physical properties of virtual objects through the fingers. However, accommodating the many degrees of freedom (DoF) of the human hand is a significant technical challenge and the desktop interfaces that are commonly available are ill-suited to multi-finger interaction. Conversely, complex grounded multi-finger exoskeletons may provide a consistent feedback to the digits, wrist, and arm, but their usage is restricted to a handful of professional applications due to a very high cost. Hence, it seems that there is currently no way to enjoy multi-finger interaction with force feedback in an affordable manner.

To make multi-finger interaction more accessible, we developed a novel approach called DesktopGlove that consists in combining two simple haptic interfaces. Through both hands, and in parallel, each interface drives a subset of the degrees of freedom involved in object manipulation. In practice, one hand is responsible for spatial displacements while the other handles grasping with the fingers (Figure 1). The force feedback resulting from the interaction is accordingly split between the hands depending on their respective duties. In this way, users can leverage affordable hardware to experience a compelling multi-finger force feedback through both hands, which was otherwise restricted to costly haptic interfaces. Our contributions can be summarized as follows:

1. We separated the degrees of freedom of one virtual hand between two simple interfaces used in parallel, as an alternative to complex input devices handling all DoF in an integrated manner. Hence one user’s hand controls the virtual fingers while the other handles global positioning. We conducted a user study comparing a traditional data glove to our approach in order to assess if its DoF separation is harmful for interaction. We additionally investigated which allocation of controls between dominant and non-dominant hands yields the best performance.

2. We split the haptic feedback resulting from multi-finger interaction between the two interfaces. In this way, each hand is subjected to forces that relate to its own frame of reference, and users perceive an exhaustive force feedback involving efforts on the wrist and the fingers. We compared different distributions of forces across the two hands in a second user study to evaluate the separation of haptic feedback in an object manipulation task.

The next section provides an overview of related work on existing haptic interfaces and two-handed interaction. Then, our approach is presented and evaluated through two user studies.

Figure 1: DesktopGlove separates the control of one virtual hand between both user’s hands: a common haptic arm handles the global motion and a custom multi-finger interface controls the virtual fingers. The force feedback is split between both interfaces so that each hand is exposed to forces that relate to its own frame of reference.
2 Related work

2.1 Haptic interaction

Traditional marker- or glove-based motion capture is a natural mean to interact in virtual worlds [36, 35]. Lately, research has gone into its generalization with regular cameras [40, 33, 23], and low-cost commercial interfaces are even available for casual applications like games. With such input devices however, the sensations associated with object manipulation are lacking. Ideally, one should perceive global forces acting on the arm and wrist, like weight and collisions, as well as finer local forces acting on individual fingers when touching virtual objects. As outlined in the following sections, most force feedback interfaces support only one or the other, apart from complex grounded exoskeletons.

Whole-hand force feedback

Most VR applications incorporating force feedback rely on compact desktop devices taking the form of robotic arms that end with a stylus or a handle. They let users control the position of a proxy typically shaped as a 3D cursor or a virtual tool, and they output global forces to the hand to reflect the physical interaction occurring in the simulation. For example, the Phantom 3-DoF device, a staple of desktop haptics, outputs linear forces [27], and bulkier 6-DoF systems may additionally output torques.

Such interfaces can constrain the global position of the hand to simulate hard surfaces, or the weight and inertia of a virtual object being manipulated. Consequently, our approach incorporates one such device to handle the control and feedback that relate to the global motion of the hand. However, an input device with an alternative form-factor is needed for delivering local efforts on individual digits and simulate object grasping, another essential aspect of multi-finger manipulation.

Multi-finger force feedback

Haptic systems delivering forces to separate fingers may be directly mounted on the user’s hand. For example, the WHIPFI exoskeleton [13] constrains the thumb and the index fingers to simulate pinching, the Rutgers-Master [7] resists four fingers with pneumatic actuators nestled inside of the palm to simulate grasping, and the encounter-type glove of Nakagawa et al. is made of robotic joints that block the fingers when a collision must be rendered [32]. The CyberGrasp, an exoskeleton that pulls the fingertips with cables, is the only device of this type that is commercially available at the moment. However, it comes with a high cost, which restricts its usage to a handful of professional applications. The mechanical complexity of such systems can be attributed to the challenge of handling many DoF on the small volume of the hand. Comparatively, we propose to separate the degrees of freedom in two clearly separated workspaces, at the intersection of the individual workspace of each hand.

For enabling truly complete force-feedback comprising global forces on the arm or wrist and local forces on individual fingers, hybrid systems combining grounded robotic arms and multi-finger exoskeletons are required. For instance, the Pure Form system is composed of a grounded robot that constrains the user’s arm and ends with two thimbles for the thumb and index finger [25]. The Haptic WorkStation is the commercial combination of a pair of Cybergrasp exoskeletons with two robotic arms for displaying global forces on both hands but, in practice, it is inaccessible because of its extremely high price. Alternatively, we propose to use two simpler haptic interfaces that, when combined, provide the same controls and feedback as such costly systems. Our approach separates the degrees of freedom involved in multi-finger manipulation between two hands. Thus, an examination of the foundations of bimanual interaction and its applicability to human-computer interaction is necessary.

2.2 Two-handed interaction

Benefits of using both hands

Firstly, two hands imply twice as many degrees of freedom and the possibility to split a single task into parallel sub-tasks, which can be beneficial for human-computer interaction. For example, Buxton et al. [9] evaluated two-handed manipulation of 2D graphical elements as well as two-handed navigation/selection in a text document: each outperformed their one-handed counterpart. Girbau et al. [14] found similar results in favor of two-handed interaction in a 3D manipulation task in which one hand controls the position of selected objects while the other hand moves the rest of the environment.

Secondly, two-handed interaction enhances spatial comprehension. Indeed, proprioception gives a sense of the position of the hands relatively to each other and relatively to the body [29, 18], which additionally reduces the need for continuous visual attention.

These different works of research indicate that two-handed interaction can be beneficial to performance in appropriate contexts. In this paper, we conduct a user study that compares our two-handed approach with a unimanual interaction technique to assess the feasibility of bimanual input for interacting through one virtual hand.
Guiard [15] developed a theoretical framework of two-handed tasks that outlines the complementarity between the dominant hand (DH) and the non-dominant hand (NDH). It states that a first component of bimanual interaction is the right-to-left reference, i.e. the NDH acts as a spatial frame of reference for the DH. This relationship is often reflected in two-handed user interfaces. For instance, Bala briskman et al. [3] controlled the view of a 3D scene with a computer mouse held in the NDH while the DH performed other tasks in parallel with a second mouse and Hinckley et al. [19] used both hand for a neurosurgical visualization application, with the NDH rotating a doll-head prop to change the user’s view and the DH holding a cutting-plane prop. In virtual sketching applications, the NDH often serves as a reference to the DH [2, 8, 20], reproducing the way we write on paper, with one hand holding a pen and the other adjusting the paper.

Another essential principle of Guiard’s framework concerns the asymmetry of the hands: the DH typically acts at a finer temporal and spatial scale than the NDH. In general, the DH has been found to perform better in tasks that require precise, small-scale, displacements, while the NDH handles motions with a large amplitude better [22]. In Section 4 of the paper, we describe a user study that was conducted to evaluate if our decomposition of the degrees of freedom of a virtual hand adheres to previous results on two-handed interaction, which applied to fewer DoF. We will also investigate how the degrees of freedom of our system should be distributed between both user’s hands.

Separating the degrees of freedom for 3D interaction

A variety of interaction techniques divides labor between two hands and implicitly separates the degrees of freedom involved in a task, either for 2D interaction [9, 22, 8, 20] or for 3D interaction [3, 19, 14, 2]. Martinet et al. [26] explicitly studied the separation of 3D degrees of freedom controlled from multi-touch input and found that the DoF separation provided better performance in a peg-in-hole task by helping users better coordinate rotation and translation. Veit et al. [38] also obtained satisfying performance by separating the different axes of rotation in a 3D orientation task. For controlling virtual hands, Achibet et al. [1] designed THING, a multi-touch system that decomposes the finger motion, controlled by performing gestures on a tablet, from the global motion of the hand model, controlled using different techniques. This provided similar performance as a technique integrating all DoF on a single device, while being preferred by participants, which suggests the feasibility of controlling a virtual hand with separated devices. In this paper, we separate the degrees of freedom of a virtual hand in a similar manner but we propose a control scheme that enables real-time interaction. Moreover, our approach additionally provides haptic feedback to both user’s hands.

Few research work focused on the distribution, between two hands, of the force feedback ensuing from 3D interaction. In an asymmetric task proposed by Boeck et al. [5], only one hand is exposed to haptic feedback: the dominant hand controls a cursor through a force feedback arm while the non-dominant hand brings objects and widget forward and only leverages proprioception. Casiez et al. studied the separation of control and force feedback between different fingers with the DigiHaptic device. They studied its effect in a 3D manipulation task where each finger controlled the motion along a different axis [11] as well as in a 3D navigation task [10]. They found that users could efficiently accommodate the separate DoF and that, while integrated control could provide better performance, the DoF separation improved accuracy.

3 DesktopGlove: separating multi-finger controls and force feedback

3.1 Current limitations and rationale

The inadequacy of current haptic hardware to support multi-finger interaction is attributable to the overwhelming number of degrees of freedom of the human hand. Because of technical considerations including bulkiness, mechanical complexity, and cost, handling them all through a single device is unpractical.

Simplifications may occur in favor of leaner designs, generally by considering only the essential functions of the hand. For example, the flexion of individual finger joints is rarely, if ever, constrained by haptic interfaces. Instead, multi-finger devices may simply pull the fingertips, which amounts to reducing the chain of joints that make a finger to a single conceptual DoF corresponding to its general curling. Still, even with such simplifications, most haptic devices only support a limited number of DoF that applies either to the whole hand or to the fingers only.

Those practical limitations can be summarized as a size problem: haptic interfaces cannot pack so many degrees of freedom on the small volume of the hand without burdening users. For this reason, we propose to distribute the degrees of freedom involved in multi-finger manipulation between two hands that operate in clearly separated workspaces. Each hand controls a specific aspect of object manipulation and receives appropriate force feedback in return. In the end, our system exposes users to the same controls and feedback as a grounded exoskeleton would, while being much more accessible.

3.2 Implementation

In this paper, we propose DesktopGlove, a bimanual setup that distributes multi-finger controls and feedback between two distinct interfaces. This design is motivated by the fact that, due to the highly articulated nature of the hand, individual haptic interfaces cannot support the many degrees of freedom involved in multi-finger manipulation without complex and costly mechanisms.

This general approach raises the question of the most appropriate distribution of degrees of freedom between the hands. In this work, we propose a novel separation that distinguishes (1) the DoF that are part of the global frame of reference of the hand from (2) the DoF that are part of its local frame of reference.

Global frame of reference

We designate one of the user’s hand to control the global frame of reference of the virtual hand he is interacting through, which consists of its position and orientation in space. Thus in practice, this user’s hand is in charge of performing coarse actions such as reaching for virtual objects, pushing them, or throwing them. The forces that are delivered to this hand relate to the interaction of the hand as a whole with the virtual environment, like gravity and forces resulting from collisions.

In our prototype implementation, a Geomagic Touch haptic arm (3D Systems, USA) provides the controls and feedback described above (Figure 3, right). Users move the virtual hand by moving the stylus of the device in a similar manner to maintain an isomorphism between the real motion of the user and its restitution in the virtual environment. A rotational offset is also applied to the hand model so that the alignment of the user’s hand holding the stylus matches that of the virtual hand.

Local frame of reference

We designate one of the user’s hand to control the local frame of reference of the virtual hand, which consists of the precise motion of its fingers. This hand is responsible for a variety of actions that require precision such as grasping, brushing fingers against an object, or squeezing it to feel its material.
In our implementation, we used a custom variant of the DigiHaptic device [12], with motors arranged in a parallel layout to handle two pinching fingers (Figure 2). Additional 3D-printed rings were installed on the levers to insert the fingers in so that fingers could be brought together or separated by the device to simulate haptic interaction. Comparatively to gripper handles that equip 7-DoF haptic devices, this system applies individual forces to each finger (i.e. our implementation has 8 DoF). Moreover, the current setup could be easily extended to accommodate a greater number of fingers to support more complex grasps. For instance, the original DigiHaptic supports three fingers and other systems from the literature that handle different numbers of fingers would also be compatible.

Distributing force feedback between the interfaces

The virtual hand that conducts the interaction is driven by a physical model that controls its posture and distributes the efforts resulting from object manipulation between the two interfaces.

The hand model itself is supported by an underlying physical skeleton made of an assemblage of rigid bodies forming the palm and the phalanges (Figure 3, Left). Physical constraints connect those segments together and apply realistic limits to the motion of each joint so that the skeleton adapts to the shape of the objects it touches while keeping a plausible configuration.

Coupling this articulated model to the pair of input devices is realized via an intermediary model that is not visible, in a manner analogous to Borst et al. [6]. This intermediary model, which consists of the ideal positions of the palm and fingertips (Figure 3, center), is responsible for driving the motion of the virtual hand. The position of the palm is governed by the haptic arm handling the global frame whereas the positions of the fingertips depend on the multi-finger device that handles the local frame. This intermediary model only serves a positional role and does not react with the rest of the environment. However, each of its part is linked through a spring-like constraint to the corresponding part of the physical hand model. In consequence, the physical model is attracted toward the intermediary model and tends to adopt a similar configuration while respecting the constraints of the virtual environment.

The magnitudes and directions of the forces to be rendered through each interface depends on the discrepancy between corresponding parts. In free space for instance, both physical and intermediary model should overlap and no feedback is sent to the interfaces. If the user pushes against a virtual object however, the intermediary model penetrates it while the physical one stays at its surface. The distance between the palms determines the feedback to be provided by the haptic arm while the distance between corresponding fingertips determines the intensity of the feedback on the appropriate lever of the multi-finger interface. Figure 4 shows examples of interaction cases and the resulting force feedback sent to the user through each device.

This physical model requires precise tuning to provide a stable and responsive interaction. As any physics-based system, the indirect relationship between different parts of the virtual hand may induce subtle unwanted motions (e.g. moving a finger slightly alters the position of the wrist) but the participants of our user studies did not report that they perceived such effects. In general, this coupling enables a plausible interaction that is consistent with the physics of the virtual environment. This opens the way for extensions that would render additional haptic properties (e.g. friction) through new hardware components (e.g. tactile effectors).

Motivations

Separating the local and global frames of reference is motivated by hardware reasons and previous results from the study of two-handed interaction:

1. Force feedback devices tend to specialize in dealing with a specific frame of reference. As outlined in the Related Work section, desktop arms provide whole-hand forces whereas multi-finger interfaces deliver within-hand efforts. In order to capitalize on the current supply of haptic hardware and provide both types of forces, we split our degrees of freedom in a manner that is consistent with the available technology.

2. Studies in the field of psychophysics have shown the asymmetry of two-handed interaction and highlighted the strengths of each hand [15]. Thus, it seems appropriate to associate each hand with a frame of reference that fits its capabilities. For instance, the dominant-hand is more suited to precise small-scale movements [22]. The user study described below evaluates which hand is best suited to the control of which degrees of freedom of a virtual hand.

3. Our approach provides haptic feedback and precise controls to the users by leveraging both their hands. Previous studies suggest that separating the degrees of freedom is a viable option for 3D interaction [1, 11, 10]. However, it is necessary to evaluate the effects of this separation on task performance since the initial premise might seem counter-intuitive in view of Jacob’s work on the separability of interfaces, which states that “the structure of the perceptual space of an interaction task should mirror that of the control space of the input device” [21]. Hence, we conducted user studies to ensure that users could effectively integrate the separated DoF in controls and in force feedback.

Benefits

Separating the degrees of freedom in this manner presents the following benefits over the existing solutions:

Exhaustive force feedback DesktopGlove exposes users to a variety of haptic effects acting both on the wrist and on the fingers, to express the various forces involved in hand-based interaction. Traditionally, such effects are individually obtained via separate haptic devices that do not work in concert but our approach enables them all through a single two-handed setup.

Common hardware The implementation that is described below is accessible and easily reproducible. It leverages a common haptic arm that is affordable and often found in research laboratories. Regarding the multi-finger interface, it is easily to replicate, as its minimalist design suggests. Moreover, various other multi-finger interfaces would be appropriate to fill this role.

Isomorphism Even though users wield two separate interfaces, they still perform the gestures that are reflected in the virtual environment. In Virtual Reality applications involving only
Figure 3: Coupling between the virtual hand and the input devices. Left: the hand model has an underlying physical skeleton (green) that interacts with the virtual environment. Center: a non-physical intermediary model is directly driven by the input devices; spring-like constraints attract the virtual hand which tends to adopt the same configuration without penetrating virtual objects. Right: the input device controls the intermediary model and output forces that depend on the discrepancy between virtual hand and intermediary hand.

Figure 4: Forces delivered by each haptic interface for different interaction scenarios. Orange arrows illustrate global forces applying to the whole hand, delivered by the haptic arm. Pink arrows illustrate local forces applying to the digits, delivered by the multi-finger device. Some manipulation tasks involve both types of feedback, like feeling the surface of an object through the fingers as well as its weight through the wrist.

4 User Evaluation

We conducted two user studies to evaluate how users handle multi-finger manipulation with separate degrees of freedom. For both studies, we measured the time to complete different tasks with a virtual hand and participants had to answer a subjective questionnaire regarding their experience with our system.

The goal of the first experiment was to evaluate how the DoF separation affected users when no force feedback was involved, and most importantly if it was harmful to interaction. To do so, they were asked to reproduce predefined hand postures. Our approach, DesktopGlove, was compared to a traditional data glove that integrates all degrees of freedom on a single hand. A side-goal of this evaluation was to assess which of the global or local frames should be controlled by the dominant and non-dominant hands.

The goal of the second experiment was to assess how separating force feedback between the two interfaces affects performance and user appreciation. Participants had to complete an object manipulation task with different distributions of force feedback. The results from this experiment are expected to provide insights into which configuration is preferable: no forces at all, forces applied on both hands or partial haptic feedback on a specific hand.

4.1 Experiment #1: separated vs. integrated controls

Apparatus

The evaluation was presented on a 24 inch screen displaying a fixed view of the virtual environment (Figure 6). The environment featured shadows providing additional depth cues helping in the task. The virtual hand controlled by participants was a realistic-looking model from the LibHand library.

In one experimental condition, participants wore a 5DT glove (Fifth Dimension Technologies, South Africa). Only the movements of the thumb and index fingers were considered and input from the other digits was ignored. Since this type of device is sensitive to user morphology, only participants whose hand size fits the glove were considered and the system was individually calibrated.

For controlling the global position and orientation of the virtual hand, a Razer Hydra (Sixense, USA) 6-DoF tracker with a 1 mm/1° spatial resolution was used. It was attached to the wrist when the data glove was used and held in the appropriate hand for the other conditions.

Our custom multi-finger device controlled the finger curling in the experimental conditions featuring our approach. The levers were arranged in a triangle layout with the central motor slightly

4LibHand, http://www.libhand.org
offset to the front of the device so that users could insert their thumb in it comfortably, and insert the index finger in the left or right lever depending on the hand they had to use at the moment. During this first user study, haptic feedback was disabled and the device only registered user’s inputs.

Participants
Twelve participants took part to the experiment. All the participants were males aged between 23 and 30 (M = 26, SD = 3) who identified their right hand as the dominant one. When asked about their experience with Virtual Reality and 3D interaction, 9 participants reported that they were familiar, 1 reported that he was moderately familiar, and 2 reported that they were not familiar.

Procedure
Participants were asked to complete a posing task that consisted in quickly reproducing certain postures with their virtual hand. Those postures were illustrated by a semi-transparent target hand that had to be overlapped. Seven postures involving various positions, orientations, and finger configurations were presented to participants in an ascending order of difficulty (Figure 5). All postures except for the first one had an horizontally mirrored variant placed on the opposite side of the environment in order to ensure fairness between the experimental conditions. Thus, pose #1 only required a translation of the virtual hand. Poses #2 and #2’ additionally required a rotation around one axis and the flexion of a single digit. Poses #3 and #3’ required a rotation around two axes and the flexion of the other digit. Finally, poses #4 and #4’ required a complex rotation around three axes and different amounts of flexion for each digit.

A trial was considered valid once the virtual hand overlapped the target hand within tolerance thresholds of 1.5 cm in position, 15° in rotation and 15% flexion. Those thresholds were chosen to ensure that users could quickly reproduce gestures while maintaining a reasonable level of precision. Under those conditions, the target hand disappeared and a blinking marker prompted the participant to go back to its starting position at the bottom of the screen, which triggered a countdown leading to the next trial.

Conditions
The goal of this first evaluation was to assess if users could efficiently control a virtual hand with separated degrees of freedom. Thus, our approach is compared in terms of performance to a traditional method that integrates all DoF on a single interface. An additional objective of this user study is to determine which hand – dominant or non-dominant – is best suited to the control of the local and global frames of reference. Therefore, participants are subjected to the three following experimental conditions that vary the roles attributed to each hand:

<table>
<thead>
<tr>
<th>Condition</th>
<th>Non-dominant hand</th>
<th>Dominant hand</th>
</tr>
</thead>
<tbody>
<tr>
<td>INTEGRATED</td>
<td>Local</td>
<td>Global + Local</td>
</tr>
<tr>
<td>SEPARATEDA</td>
<td>Global</td>
<td>Local</td>
</tr>
<tr>
<td>SEPARATEDB</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

INTEGRATED — All of the controls are handled by the dominant hand, equipped with a data glove. Curling the fingers curls those of the virtual hand correspondingly. Translating and rotating the hand in space move the virtual hand accordingly. This direct and natural mode of interaction is expected to provide an upper bound in terms of performance.

SEPARATEDA — In this variant of our approach, controls are split between two hands. The non-dominant hand controls the flexion of the virtual fingers through the multi-finger device that has been described previously. The position of the virtual hand is updated from the real position of the participant’s dominant hand, which holds a spatial sensor.

SEPARATEDB — In this second variant, controls are also split between two hands but the interfaces are reversed: the non-dominant hand controls the global position and orientation while the dominant hand controls curling. Even though the devices are swapped, the virtual hand is still right-handed and the user’s thumb (respectively index finger) still controls the virtual thumb (respectively index finger).

Experimental design
The independent variables of the experiment were the TECHNIQUE (INTEGRATED, SEPARATEDA, SEPARATEDB), POSE (#1, #2, #2’, #3, #3’, #4, #4’) and REPETITION (4 different trials for each pose and each technique). The seven poses to reproduce were always presented in the same ascending level of difficulty since pre-tests showed that less experienced users would experience difficulties if they started directly with more complex poses. The order of the techniques was counterbalanced among the participants using a Latin square. The duration of the experiment was approximately 45 minutes including breaks. In total, we had 12 participants × 3 techniques × 7 poses × 4 repetitions = 1,008 trials.

Collected data
Completion time is the main measure and is defined as the time taken between the beginning of each trial and the time when participants successfully matched the virtual hand with the target hand within the tolerance thresholds. At the end of the evaluation, participants filled a subjective questionnaire to rate each technique in terms of global appreciation, ease, speed, accuracy, comfort, and fatigue on a 5-point Likert scale. A score of 5 for these criteria means a very positive rating except for fatigue where it means that the technique was very tiring (a rating of 1 means that it was not tiring at all). The participants were also asked to order the techniques by personal preference.
A mixed repeated measures ANOVA showed a significant effect of TECHNIQUE ($F(2, 976) = 8.36, p < 0.001$) and POSE ($F(6, 976) = 26.81, p < 0.001$) on completion time (Figure 7) as well as a significant TECHNIQUE \times POSE interaction ($F(12, 976) = 4.21, p < 0.001$).

A post-hoc analysis using a Tukey test revealed significant differences between the INTEGRATED technique and the two other techniques ($p < 0.001$ for SEPARATEDA, $p < 0.004$ for SEPARATEDB) (INTEGRATED=9.63s, SEPARATEDA=7.69s, SEPARATEDB=7.48s). Post-hoc analysis also showed significant differences between POSE#2 and the other poses ($p < 0.001$) as well as between POSE#3 and the other poses ($p < 0.001$). There is no significant difference between POSE#2 and POSE#3. There is also a significant difference between POSE#1 and POSE#2$'$ ($p < 0.001$) and POSE#1 and POSE#3$'$ ($p = 0.01$ ($#1=5.32s, #2=11.58s, #2'=7.73s, #3=11.67s, #3'=7.54s, #4=6.26s, #4'=7.79s$).

Concerning the interaction effect, post-hoc analysis revealed that the INTEGRATED technique was significantly slower than the SEPARATEDA technique for POSE#2 ($p = 0.009$) and slower than the SEPARATEDB technique for POSE#3 ($p < 0.001$). There was no other significant effect.

![Figure 7: Completion time for TECHNIQUE and POSE. Error bars represent 95% CI.](image)

A Friedman analysis on the subjective questionnaire showed no significant effect for the global appreciation, ease, and speed criteria. A significant effect was found for the accuracy criterion ($maxT = 2.90, p = 0.01$). Post-hoc analysis revealed that the INTEGRATED technique (Median=3) was perceived as less accurate than SEPARATEDA (Median=4, $p = 0.01$). A significant effect was also found for the comfort criterion ($maxT = 2.83, p = 0.01$). Participants felt that the two SEPARATED techniques (Median = 4 and 3) were more comfortable than the INTEGRATED technique (Median = 2, $p = 0.01$ and $p = 0.04$). A significant difference was also found for the fatigue criterion ($maxT = 2.67, p = 0.02$). Participants felt more fatigue when using the INTEGRATED technique (Median = 3, $p = 0.02$) compared to the SEPARATEDA technique (Median = 2).

Finally, when they were asked to state which technique they preferred, eight participants chose SEPARATEDA as their favorite technique, two participants chose SEPARATEDB and two participants chose the INTEGRATED condition.

Summary
Overall, the two SEPARATED techniques performed well compared to the INTEGRATED technique. Subjective answers also showed that the SEPARATED techniques were both felt as more comfortable than the INTEGRATED technique, and that the SEPARATEDA technique was less tiring than the INTEGRATED technique.

POSE#2 and POSE#3 took significantly more time to complete than the other poses, especially because the INTEGRATED technique was significantly slower for these specific tasks compared to the SEPARATED techniques.

Finally, the SEPARATEDA technique, i.e., controlling the fingers with the non-dominant hand and controlling the position with the dominant hand, was predominantly preferred by participants.

4.2 Experiment #2: object manipulation with force feedback

Apparatus
This experiment was conducted in the same environment as the previous evaluation. In all conditions, users interacted through our bi-manual setup, DesktopGlove, with the layout that was preferred by participants in the first user study. Thus, the virtual fingers were controlled through the multi-finger device with the non-dominant hand, as in the previous experiment, and the position and orientation of the virtual hand was controlled through a force feedback arm with the dominant hand. For this second user study, haptic feedback was enabled.

Population
Twelve participants took part to the experiment (10 males, 2 females). They were aged between 22 and 31 ($M = 26.5, SD = 2.9$) and identified their right hand as the dominant one. When asked about their experience with Virtual Reality and 3D interaction, 7 participants reported that they were familiar, 3 reported that they were moderately familiar, and 2 reported that they were not familiar.

Procedure
Participants were asked to complete a docking task which consisted in placing a virtual toy cube in certain configurations indicated by a semi-transparent target. They first had to grasp the cube, which was on the floor, and then dock it on the target (Figure 8). If necessary, they could drop the cube and grab it from another angle to complete complex rotations in several steps.

Three pairs of targets involving different orientations had to be overlapped. Each pair consisted of a same pose, either placed on the left of the environment (#n) or on the right (#n$'$), at the same distance from the starting position. Poses #1 and #1$'$ only required to grab and translate the cube. Poses #2 and #2$'$ additionally required a leftward rotation of 90$^\circ$ so that the left side faced the participant. Poses #3 and #3$'$ required a downward rotation of 90$^\circ$ so that the top side faced the participant. The cubes featured colored numbers on their faces as an additional visual cue.

A trial was considered valid when the toy cube overlapped the target within a tolerance threshold identical to the first experiment. Then, the cube and the target disappeared and users had to return to their initial position to trigger a countdown leading to the next trial.

![Figure 8: The second experiment required to dock a toy cube with the appropriate orientation. Depending on the experimental condition, participants were subjected to various distributions of force feedback between their two hands.](image)
Conditions
The goal of this second experiment was to evaluate how users could handle the separation of force feedback between two interfaces both in terms of control and appreciation. Regarding control, it is indeed necessary to assess if force feedback has an impact on performance. Regarding appreciation, it is necessary to ensure that users integrate those separated degrees of freedom well and that the resulting sensations are clearly understandable. Hence, we exposed participants to the following distributions of force feedback between the two hands:

<table>
<thead>
<tr>
<th>Condition</th>
<th>Local forces</th>
<th>Global forces</th>
</tr>
</thead>
<tbody>
<tr>
<td>NONE</td>
<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td>FINGERS</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>WRIST</td>
<td>✗</td>
<td>✓</td>
</tr>
<tr>
<td>BOTH</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

Local forces consisted of opposite forces delivered on the fingers of the non-dominant hand, to simulate the sensation of grasping the cube. When an object was grasped, opposite forces were delivered to the thumb and index finger to keep them at its surface.

Global forces consist of the efforts delivered to the wrist of the dominant hand, and include the weight of the cube and collisions with the floor. The intensity of the downward force was adjusted to be consistent with the visual appearance of the object (a wooden toy cube). A large upward force was applied by the device if participants attempted to pass through the floor.

Experimental design
The independent variables were the Feedback (NONE, FINGERS, WRIST, BOTH), Pose (#1, #1’, #2, #2’, #3, #3’) and Repetition (3 different trials). The order of the types of feedback and poses was counterbalanced among the participants using a Latin square. The total duration of the experiment was approximately 20 minutes. In total, we had 12 participants × 4 types of feedback × 6 poses × 3 repetitions = 864 trials.

Collected Data
Completion time is the main measure and is defined as the time taken between the beginning of each trial and the time when participants successfully matched the virtual cube with the target cube within the tolerance thresholds. At the end of the evaluation, participants filled a subjective questionnaire to rate each technique in terms of global appreciation, realism of the feedback, accuracy, comfort, fatigue, ease, the perception of weight, perception of contact and perception of shape on a 5-point Likert scale. A score of 5 for these criteria means a very positive rating except for fatigue. The participants were also asked to order the types of force feedback by personal preference.

Results
A mixed repeated measures ANOVA showed a significant effect of Pose (F(5,844) = 59.83, p < 0.001) only on completion time. A post-hoc analysis using a Tukey test revealed significant differences between all the poses, except between Pose#1 and Pose#2, and between Pose#2 and Pose#3. The mean values were: None=10.84s, Wrist=11.73s, Fingers=11.18s, Both=10.54s for the Feedback, (#1=8.72s, #1’=6.46s, #2=11.61s, #2’=9.73s, #3=17.43s, #3’=12.47s).

A Friedman analysis on the subjective questionnaire showed no significant effect for the ease criterion. A significant effect was found for the global appreciation criterion (maxT = 2.58, p = 0.0048). Post-hoc analysis revealed that the Fingers feedback (Median = 4) had a higher rating compared to the Wrist feedback (Median = 3, p = 0.0048). A significant effect was also found for the realism and the accuracy criteria (maxT = 3.46, p = 0.003) and (maxT = 2.83, p = 0.03) respectively. Post-hoc analysis revealed that the BOTH feedback (Median = 4) was found more realistic than the NONE feedback (Median = 2, p = 0.003). For the accuracy criterion, the same significant effect was found, the BOTH feedback (Median = 4) being more accurate than the NONE feedback (Median = 3, p = 0.02). The Friedman analysis revealed also a significant effect for the comfort criterion (maxT = 2.78, p = 0.03). The post-hoc analysis showed that the Fingers feedback (Median = 4) was found more comfortable than the Wrist feedback (Median = 3, p = 0.03). Finally, a significant effect was found for the fatigue criterion (maxT = 2.71, p = 0.03). Post-hoc analysis revealed that both the Wrist feedback (Median = 4) and the BOTH feedback (Median = 4) were felt as more tiring than Fingers feedback (Median = 2, p = 0.03 and p = 0.02). Boxplots of the different criteria are shown in Figure 9.

Concerning the perception criteria, we found a significant effect for all of them: perception of weight (maxT = 4.21, p < 0.001), perception of contact (maxT = 3.54, p = 0.002), perception of shape (maxT = 4.11, p < 0.001). The post-hoc analysis revealed that the Wrist feedback and the BOTH feedback were found as significantly better to perceive weight (Median_{wrist} = 1, Median_{wrist} = 1.5, Median_{wrist} = 4, Median_{wrist} = 4) and contact (Median_{contact} = 1, Median_{contact} = 1, Median_{contact} = 4, Median_{contact} = 4) compared to the NONE and Fingers feedback. Concerning the perception of shape, the post-hoc analysis revealed that the BOTH feedback (Median = 4) was found as better to perceive the shape compared to NONE (Median = 1, p < 0.001) and Wrist (Median = 1.5, p < 0.001).

Finally, when they were asked to state which technique they preferred, 7 participants chose BOTH as their favorite types of force feedback, 3 participants chose FINGERS, 1 participant chose WRIST and 1 participant chose NONE.

Summary
The quantitative evaluation did not reveal any significant effect on task performance between the different types of feedback, which indicates that the separation of the force feedback between two hands...
did not disrupt the interaction in the context of this specific docking task. The subjective evaluation gave significant information concerning the participants appreciation with respect to different criteria. Thus, force feedback on both hands was found to be more realistic and more accurate than no haptic feedback in both hands. Haptic feedback on the wrist of the dominant hand was found to be more tiring than with the fingers feedback, whatever the feedback in the non-dominant hand. Thus, the use of a haptic device increased the perceived fatigue of the participants. On the contrary, the use of haptic feedback in the dominant hand seemed to increase the perception of weight, contact and shape compared to no haptic feedback in the dominant hand, thus improving the perception of the objects when manipulating them in the virtual scene.

Participants commented that “it was easier to grab the cube and place it” and “it felt natural” for the use of the both feedback. The use of the fingers feedback was felt to “ease the grasping, especially when the cube is occluded by the hand”.

5 DISCUSSION

Controlling separated DoF — Our design of DesktopGlove raised the main question of the users’ ability to coordinate both hands to control the separated degrees of freedom of one virtual hand. Previous results on this topic showed that the degrees of freedom of a virtual hand could be separated between several interfaces used sequentially [1]. The results of our first experiment complemented those results by showing that, in a posing task, users are able to control the separated degrees of freedom in parallel without loss of performance compared to a data glove with integrated DoF. A subjective study also showed the higher preference for DesktopGlove in terms of fatigue and comfort. The low scores of the data glove in this user study could be explained by the variable accuracy of such interfaces depending on the user’s morphology [1]. Moreover, the nature of the experiment required users to reproduce postures in the air with the glove, which may make difficult the adjustment of specific degrees of freedom without affecting the others, whereas DesktopGlove provided added support and the ability to separate the DoF, especially for the virtual fingers. Those positive results apply to the static posing task that participants had to complete and future user studies could investigate the applicability of DesktopGlove to more complex contexts involving continuous motion of both the wrist and fingers, such as virtual assembly or virtual surgery training.

Dominant and non-dominant hands — We additionally found that the preferred configuration relies on the use of the multi-finger device with the non-dominant hand and the spatial tracker with the dominant hand. This result may seem to go against the literature on two-handed interaction, which states that the dominant hand is better suited to deal with tasks requiring precision. However, with our system the non-dominant hand does not change position and only the fingers move, which might explain this difference. Moreover, several participants mentioned that positioning of the hand was the part that required the most accuracy in the task of the experiment. With future iterations of our approach, handling a greater number of fingers for instance, user studies could evaluate if those results still apply. Indeed, the additional degrees of freedom brought with new fingers could switch the complexity load on the hand controlling them and it might be beneficial to reverse the layout in such situations.

Perceiving separated forces — The second experiment answered the question about the quality of perception of separated forces. We observed that users were not disoriented by the force feedback: there was no loss of performance when separating the forces between two hands. The lack of significant difference between no force feedback and the other distributions could be due to the nature of the task thus more complex interaction scenarios, such as virtual assembly, could be evaluated in future studies. Participants rated the force feedback on both hands higher than the other conditions, in terms of precision and realism. Moreover, the use of a haptic feedback in the dominant hand was felt as better to perceive the weight, the contact, and the shape of the manipulated objects. In the end, participants predominantly preferred being exposed to full force feedback on both hands and mentioned that it reinforced realism and it helped them to be more accurate without looking at the hand model.

Greater number of fingers — The implementation of DesktopGlove that we presented combines a generic multi-finger arm with a custom multi-finger interface derived from the DigiHaptic [12]. It currently supports two pinching fingers that are controlled and receive force feedback separately to enable the grasping of virtual object. Our approach could be extended to support a greater number of fingers and thus support a wider range of grasps, either by leveraging existing multi-finger interfaces [30, 24] or by designing new devices to handle more digits. For instance, the original DigiHaptic device already provides haptic feedback to three separate fingers. It would also be necessary to conduct user evaluations to quantify the number of fingers effectively required for a meaningful interaction, and if they all require the same level of control and haptic fidelity.

Bimanual interaction — DesktopGlove distributes the degrees of freedom of one virtual hand between two hands. In consequence, users are restricted to unimanual tasks in the virtual environment. Nevertheless, a variety of actions requires the coordinated use of both hands, for instance using a hammer with one hand and holding a nail with the other. This limitation is critical for virtual training applications in which trainees must learn procedures through practice, as interacting through a single hand would teach only half the procedure. A possible solution could be to display a second, autonomous virtual hand that would assist the dominant one during bimanual tasks and illustrate the other half of the procedure. This first idea could be extended furthermore with new bimanual control schemes for either switching between virtual hands depending on the focus of the task, or leveraging our bimanual setup to control and perceive the action of each virtual hand during two-handed subtasks.

Potential applications — DesktopGlove opens the way to novel force feedback interfaces combining haptic interfaces in both hands for better handling multi-finger manipulation. It could be used in domains with complex use cases where objects should both be grasped and moved such as virtual prototyping and virtual training. Other possible applications such as video games, a domain in which expensive peripherals are impractical, or teleoperation, which currently relies on complex robots, could benefit from its affordable and transportable multi-finger haptic feedback.

6 CONCLUSION

We presented DesktopGlove, a new multi-finger force feedback interface for controlling the grasping, position, and orientation of a virtual hand, together with force feedback both on the hand and fingers. This approach is built on the core idea of separating the degrees of freedom of one virtual hand between both user’s hands. As a result, users can be exposed to an exhaustive haptic feedback, which was otherwise restricted to costly grounded exoskeletons. Compared to 7-DoF gripper interfaces, DesktopGlove delivers individual forces to each finger, with the possibility to easily support additional digits whereas gripper devices are limited in the number of actuators placed on their end-effector due to volume constraints.

The results of a first experiment showed that the separated degrees of freedom did not harm the user’s performance in a posing
task where our approach was preferred by users compared to a data glove. A second experiment showed the consistency of the separated force feedback in a docking task, as the users overall preferred full force feedback on both hand and fingers. Hence, the results of this work open the way to the development of mechanically simplified and accessible haptic interfaces providing a rich haptic feedback without sacrificing performance or expressiveness.

ACKNOWLEDGEMENTS
This work was supported by ANR (MANDARIN project, ANR-12-CORD-0011).

REFERENCES