Identifying Virtual 3D Geometric Shapes with a Vibrotactile Glove

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A haptic display based on a vibrotactile glove and multiple points of contact gives users an enhanced sensation of touching a virtual object in cases with no visual guidance. Without the need for complex, expensive force-feedback mechanisms, the display produces gentle vibrations that do not tire the user.

Computer interaction has jumped off the screen thanks to the introduction and spread of affordable depth sensors such as Kinect, Xtion, and Leap Motion. Moving away from traditional user interfaces based on the mouse and keyboard, however, has resulted in a loss of perceptual cues. It is not only that the shape and layout of the keys on a keyboard are easily perceived by the user's sense of touch, but also that the force feedback that occurs as the user presses them provides confirmation of their activation. This, touch and force feedback, is usually referred to as haptic feedback. In contrast, interfaces projected onto a table, wall, glass, or smoke or those turned into virtual 3D images with the appropriate glasses all lack haptic feedback. Users attempting to manipulate the objects in the projected image cannot feel anything solid.

Thus, introducing haptic feedback can help improve this new generation of interfaces. In some applications, such as those that require users to manipulate one object while maintaining focus on another, such feedback is essential. Ideally, a haptic device should allow us to touch virtual objects in the same way as real ones in our daily lives, which requires developing systems that allow us to feel the object's surface and thus its hardness, temperature, weight, volume, and shape.[1] Creating such a device is challenging, and current haptic solutions typically focus on just a part of the problem. (See the "Related Work in Haptic Feedback" sidebar for more details.) To complicate matters, a haptic device should also be light, be able to deal with a large volume of work, and allow free hand movements so users can interact with floating, mid-air interfaces.

This article focuses on helping users perceive the shape of virtual 3D objects through haptics, a task that is far more complex than vision. Susan Lederman and Roberta Klatzky identified two main exploratory procedures: *enclosure*, which is performed by more than one finger or even both hands, and *contour following*, which may be done by one or more fingers.[1] However, the information provided by haptic devices is limited, which in turn limits the possible exploratory procedures. For this reason, identifying objects without visual information is a demanding task that can be used to evaluate the limits and possibilities of a haptic system.

Here, we present a multiple-contact-point haptic display based on a glove, 12 vibrotactile actuators, and an optical tracking system that is suitable for many applications, especially for next-generation interfaces. The proposed haptic display is lightweight and inexpensive (because it is based on consumer vibrators), and it can be used in workspaces as large as optical tracking allows, typically from the desktop to spaces as big as a room. Using a simple version of this glove, we previously demonstrated that it can be used to recognize 2D textures such as those found on

 Published by the IEEE Computer Society

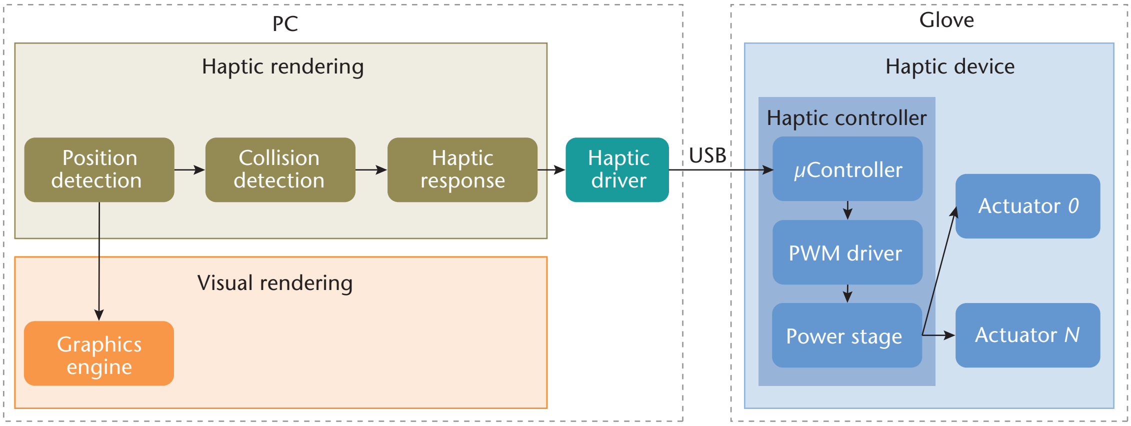

Figure 1. System architecture. The haptic rendering module captures the position of the user's hand and calculates the haptic feedback needed for each actuator. The haptic driver transmits this information to the haptic device module.

object surfaces.[2] In this article, we go further and demonstrate experimentally that it can also be used to recognize the shape of virtual 3D objects. In addition, thanks to multiple actuators suitably placed in the glove, together with the careful control of vibration at both the controller and haptic rendering level, our device supports more exploratory procedures without the need for the force-feedback mechanisms commonly available in other single-contact-point devices.

Haptic Display

The proposed haptic display is based on vibrotactile technology. Although the sensation is not equivalent to a natural sensation with real objects, the user soon learns to reinterpret it. An array of actuators is arranged on a nylon glove and connected to a microcontroller to produce localized vibrations on the palm and fingers. We focused on producing a comfortable sensation by keeping the amplitude of vibration below 0.7 G, with an average oscillation frequency of 120 Hz. Key vibration pulses are produced only when necessary to avoid saturating the touch channel, which would lead to a reduction in sensitivity.

The system's basic architecture, which is depicted in Figure 1, is based on the one proposed in earlier work.[3] The haptic rendering module resides in the computer and is used to capture the position of the user's hand and calculate the haptic feedback needed for each actuator. This information is transmitted by the haptic driver to the haptic device module. The driver provides a set of functions that are contained in a dynamic link library (DLL) to establish new values for the vibrators. The haptic device is the hardware responsible for producing the vibrations. A custom communication protocol defines low-level communications with the microcontroller through a USB interface.

The visual rendering module used by the operator graphically depicts the user's hand and the virtual objects. For this, we used the open platform Ogre. The haptic and visual rendering loops, running at 480 and 60 Hz, respectively, are decoupled due to the haptic channel's higher update requirements.

Haptic Device

Each transducer consists of a small electric motor with an eccentric mass attached to it. When the mass rotates, the movement produces a vibration that is felt by the user. We often refer to this kind of actuator as an eccentric rotating mass (ERM).

Figure 2a shows the actuator array layout on the glove, with one placed under the glove fabric (we used Samsung L760 actuators). We analyzed several other configurations before choosing the

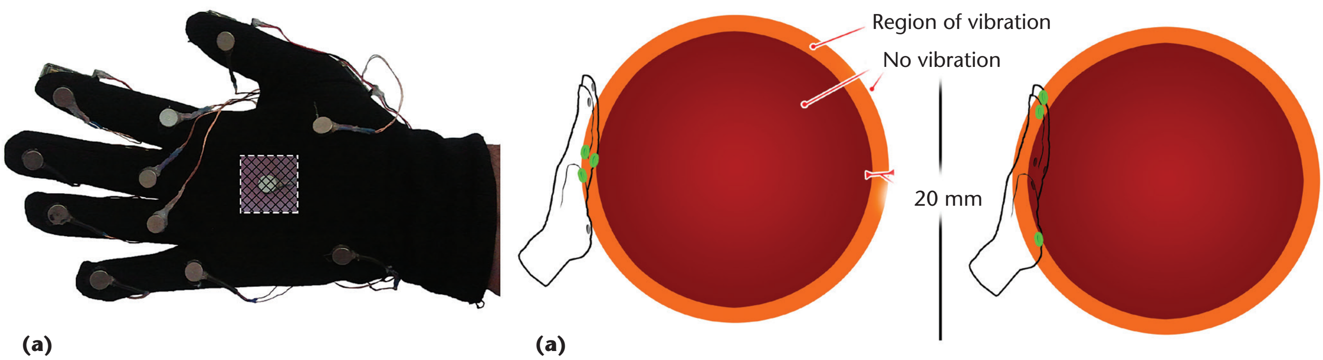

Figure 2. Haptic device. (a) Actuators attached to the glove fabric. (b) A collision with the virtual object causes different actuators to activate. The green dots indicate active actuators.

Related Work in Haptic Feedback

Other research groups have tried to add haptic feedback to interfaces based on hand tracking by developing their own haptic displays. Technologies based on ultrasounds,[1,2] air streams,[3] and pin-matrix[4] allow interaction with a bare hand, but they are too complex to scale to large workspaces. Wearable solutions do not suffer from this problem but can be cumbersome. For instance, Valentino Frati and Domenico Pratichizzo placed three motors, strings, and a small rigid piece at the tip of each finger.[5] In their approach, the motors are on the nail, the rigid piece is on the fingertip, and the tactile feedback is produced by driving the motors to wind the strings, which pull from the ends of the piece and then press the fingertip.

Other researchers have chosen vibratory motors for their projects. Elias Giannopoulos and his colleagues combined a vibrotactile glove with a Kinect sensor.[6] However, they only tracked the position of the whole hand, instead of each finger, as in our system. Much like our work, they studied the perception of shapes with their version of a haptic display, although it was only a preliminary experiment on 2D shapes, instead of the 3D shapes used in the present study.

We have found only a few previous works that try to analyze virtual 3D shape perception, all of which use force-feedback technologies. In particular, several experiments used single-contact-point hardware, especially with Phantom devices,[7,8] and other studies attempted to include a multipoint device.[9]

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final actuator locations. The first configuration had only five actuators, one on each fingertip. However, it was difficult for users to recognize objects with this configuration. We therefore added additional actuators in each finger to help users recognize flat surfaces. To help users perceive curved surfaces, other actuators were added to the palm, one of which was placed under the fabric to conform to the shape of the hand (see Figure 2a). We also tested other layouts and configurations with a larger number of actuators, but because of the size of the transducers and the propagation of vibrations through the glove fabric, performance did not improve.

This actuator configuration in Figure 2 allows different strategies to be used to identify surfaces. Figure 2b shows the operation of the different actuators (in green) when touching a curved surface.

All the actuators are connected to a haptic controller that consists of a microcontroller, a pulse width modulation (PWM) driver, and a power stage. The controller is connected to the PC through a USB connection and receives the desired vibration level for each channel once a millisecond. The microcontroller generates the electrical signals to drive the actuators using several techniques implemented in the haptic driver that are therefore transparent to the developer of the haptic glove.

Driving an ERM actuator can be simple because only direct current is needed to drive the motor to produce a vibration. However, we used multiple techniques to produce different vibration levels and to improve the actuator response and hence reduce its latency. These techniques are widely used in the industry, but are surprisingly absent in the vibrotactile controllers made by the research community.

The first technique we implemented, PWM, is commonly used to change the voltage of the actuators and hence the intensity of the vibration. PWM consists basically of switching on and off a digital signal at a high frequency to create a rectangular pulse wave. The pulse width, or the ratio between the time the signal is on and off, defines the average value of the voltage. Because the motors have inertia, this signal is smoothed, producing a change in speed and therefore in vibration intensity.

However, this intrinsic inertial nature has some limitations that restrict the response of the actuators. When the motor is stationary and a voltage is applied, the time required to start vibrating is up to 150 ms, as Figure 3a shows, which produces high latency in interactive systems. To reduce this time, we used a technique called *pulse*

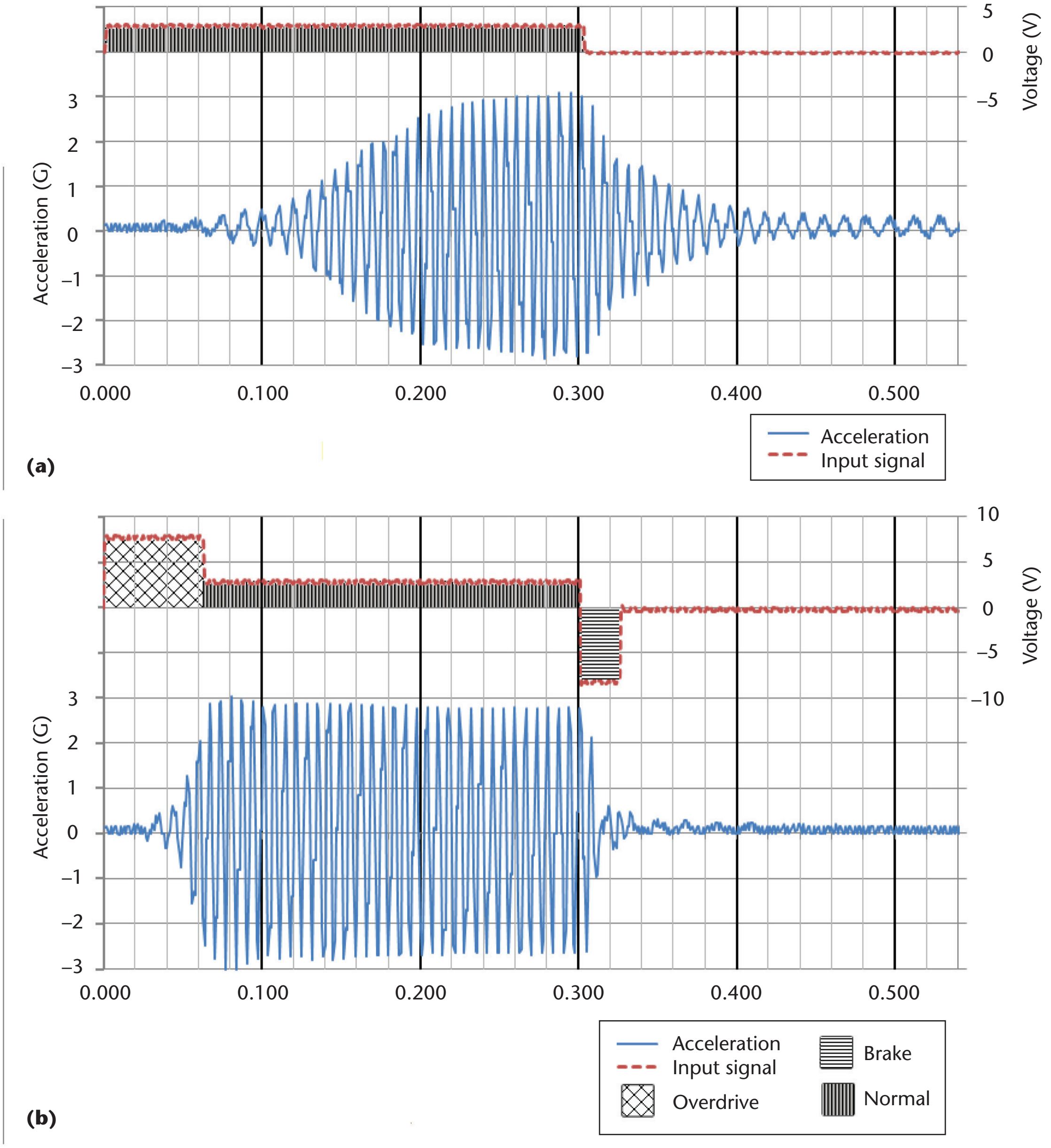


Figure 3. Advanced driving techniques measured with an accelerometer. (a) A standard vibration pulse results in up to 150 ms latency. (b) Applying overdrive and active braking reduces latency to about 25 ms.

overdrive, which consists of applying a short high-voltage pulse. The motor starts spinning faster and reduces latency to about 25 ms. Figure 3 shows this improvement and how a standard vibration pulse (Figure 3a) benefits from the overdrive (Figure 3b) in the first 60 ms. This technique is critical when a low vibration level is desired but the corresponding voltage is not high enough to start the motor.

The last technique is a variation of the pulse overdrive and is used to stop the motor. When stopping an actuator, setting its voltage to zero will make it run down slowly while it dissipates its kinetic energy, as Figure 3a shows. Instead, a reverse voltage pulse can be applied to halt it, a process that considerably improves the crispness of the perceived sensations and reduces response latency.

Using the PWM, overdrive, and active braking techniques, we can fine-tune the system to prevent the glove from producing annoying vibrations. Instead, users feel gentle sensations that provide information about the object being manipulated. –

Haptic Rendering

Kenneth Salisbury and his colleagues explained that “Haptic-rendering algorithms compute the correct interaction forces between the haptic interface representation inside the virtual environment and the virtual objects populating the environment.”[3] This involves obtaining the positions of the user

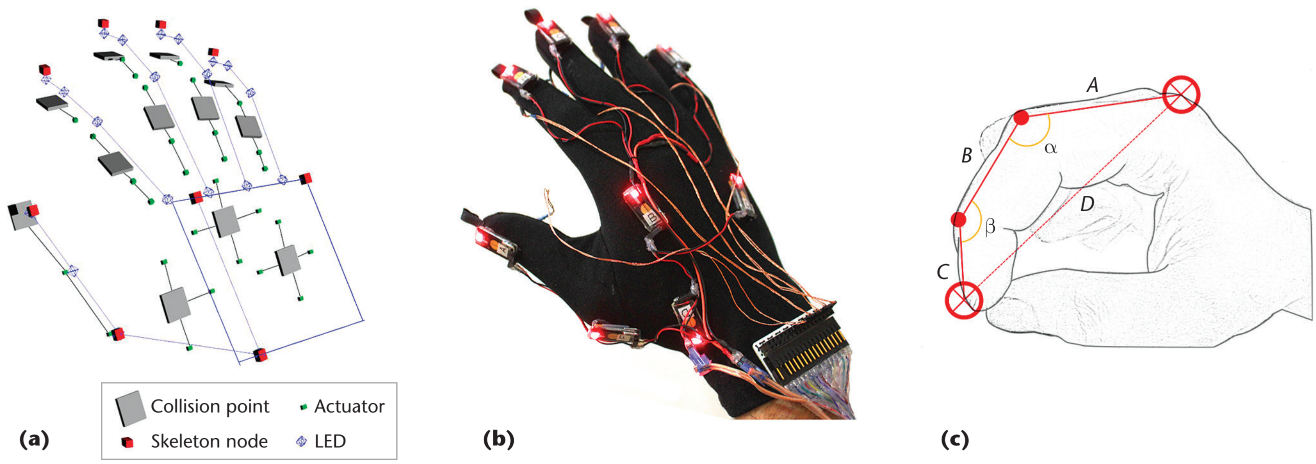


Figure 4. Hand position detection. (a) A skeleton model is calculated by the inverse kinematics algorithm. (b) Position of the LED markers used by the tracking system. (c) Diagram used to calculate the virtual skeleton from the position of the markers.

and the virtual objects. The position information is used to check for collisions between the user and the objects in the virtual environment. If a collision is detected, the haptic rendering module will compute the appropriate haptic feedback that will be provided to the user through the actuators.

Therefore, the haptic rendering process consists of three different tasks: determining the user's position, evaluating a possible collision between the user and the objects in the scene, and calculating the haptic stimulus. This last task depends on the type of physical device the system is using. In our case, we had to translate some force stimuli into vibrotactile ones.

Position Detection

The first task is determining the position and orientation of the hand and the virtual objects in space. To this end, we used a PhaseSpace Impulse optical tracking system (www.phasespace.com), which can track multiple LED markers at 480 Hz by means of a constellation of cameras and a triangulation algorithm.

A virtual hand model composed of an articulated skeleton is used for both the visual representation and to determine the position of the actuators in relation to the hand (see Figure 4a). This model is updated with the information provided by the tracking system, which determines the position in space of nine LEDs attached to the glove (see Figure 4b). Three markers situated on top of the hand are used to calculate the global orientation of the hand. In addition, one marker is situated at the end of each finger, and one more in the metacarpal region of the thumb because of its extra degree of freedom. Because not every articulation of the hand has a marker, we use an inverse kinematics algorithm to calculate the virtual skeleton (see Figure 4c). Crossed circles indicate LED positions. Segment lengths A, B, and C are constant, whereas D is calculated through the tracking system. The algorithm calculates the angles α and β, which for simplicity are assumed to be equal.

Although we use a marker-based constellation of cameras, different options are appearing on the market that could be used in a domestic environment. For example, depth cameras can be used to extract hand gestures.[4] For example, the 3GearSystems SDK uses one or two depth cameras to perform arbitrary tracking of 10 fingers. A leap motion controller is another possible alternative, although the workspace is smaller. We are also currently evaluating a low-cost optical tracking system that uses several Nintendo Wiimote peripherals to track infrared markers.

Collision Detection

Once the computer is aware of the position, orientation, and gesture of the user's hand, it must calculate the vibration intensity of each actuator depending on the collision with the virtual object. Ideally, this task will be executed up to a thousand times per second to give the user a realistic sensation and avoid instabilities in force-feedback devices. In our case, the haptic loop runs at 480 Hz and is limited by the tracking system. In practice, this is a good refresh rate for a vibrotactile device, and little improvement can be obtained by increasing it because of the inertial nature of the actuators and the open loop algorithm to control tactile feedback.

When complex objects are used, it is necessary to accelerate the collision calculations using techniques like space subdivision and/or voxelization so that they can be performed in real time. In our case, the use of simple objects let us create mathematical expressions to calculate the collisions in constant time with high precision.

The collision algorithm determines the distance of each actuator in the virtual environment from the object's surface. That is, a positive value indicates it is inside the object, and a negative value that it is outside.

Because the density of the actuator array is low, we make use of the phantom-sensation phenomenon.[5] This psychophysical illusion is produced when two adjacent actuators are stimulated, creating a subjective perception of an actuator located between them. Thus, the user feels a continuous vibration wave travelling between two vibrators when we progressively increase the vibration intensity of one actuator while decreasing the other at the same time. To create this sensation, each actuator has several associated collision points (up to five) mapped to the virtual representation of the hand. Figure 4 shows our collision points and the associated actuators.

Haptic Response

Once the penetration depth has been calculated for each collision point using the collision algorithm, the maximum level of penetration of the associated actuator is calculated as follows:

$$P = \max_{0 \leq x < n} \text{depth}_i * \text{weight}_i$$

The weight is a value associated with each collision point that depends on its distance from the actuator. Therefore, when the user moves a hand through the outline of an object, there is a soft transition between consecutive actuators, creating a feeling of continuity despite the low resolution of the array.

The calculation of the vibration intensity follows Hooke's law in order to make it proportional to the penetration level of the virtual object: $I = k * P$.

We tested different approaches to haptically render the shape of the virtual objects. After the first evaluation stage, we detected an improvement in the success rate when hollow objects were used (see Figure 2b) because this helped users follow the contour. In previous tests, it was more difficult for users to identify the contour of solid objects when the actuators continuously vibrated inside them because the users could not easily tell whether they were touching the contour or the inside of the object. If the width of the contour of a hollow object is too small, however, it is also difficult to follow and keep one or more actuators inside it. After this first evaluation stage, we defined empirically the object wall as a 2-cm region. A vibration is produced when a collision point associated with a vibrator is within this region.

Finally, when the user touches the virtual object's surface, a vibration pulse, proportional to the speed and the angle of impact, is generated to simulate the surface impact. It is important to include this technique in the interaction because it not only adds a degree of realism but makes it easier for the user to determine which part of the hand collides with the object. Thus, when a flat surface is touched with an open hand, the user feels all the vibrators activate at the same time. A curved surface, on the other hand, would activate different actuators in sequence (see Figure 2a).

Experiment

The main goal of this experiment was to assess whether the proposed device and the techniques implemented improved the range of applications for vibrotactile technology, making it possible to identify virtual 3D shapes, a task that has traditionally been restricted to force-feedback devices. Although haptic feedback is usually added to complement the visual channel, enhance user immersion, or improve the performance of manipulative tasks, when evaluating the capabilities of new haptic devices, visual guidance should not be available. Thus, the participants in our experiment could not see a graphical representation of the objects during the tests, but could only touch them. The absence of a visual cue and force-feedback guidance therefore increased the task complexity.

Method

The evaluation of the proposed device was divided into two stages. The first allowed us to redesign the experiment on the basis of the participants' recommendations, and the second to evaluate the capacity of the device to allow users to recognize virtual 3D shapes.

The first stage consisted of a brief pilot study with three subjects to analyze the experiment and identify any shortcomings. These users were designers from our group with extensive experience in developing virtual reality systems. First, we identified a need for physical paper models because the participants indicated that it was difficult to create a mental image of the virtual objects. The main problem was not the object's shapes but their size and proportions. Second, because of the problems observed in identifying solid objects, the participants recommended creating a hollow version of the objects to make it easier to follow their contours. As we discussed earlier, we empirically established the width of the contour after several tests. The participants also suggested

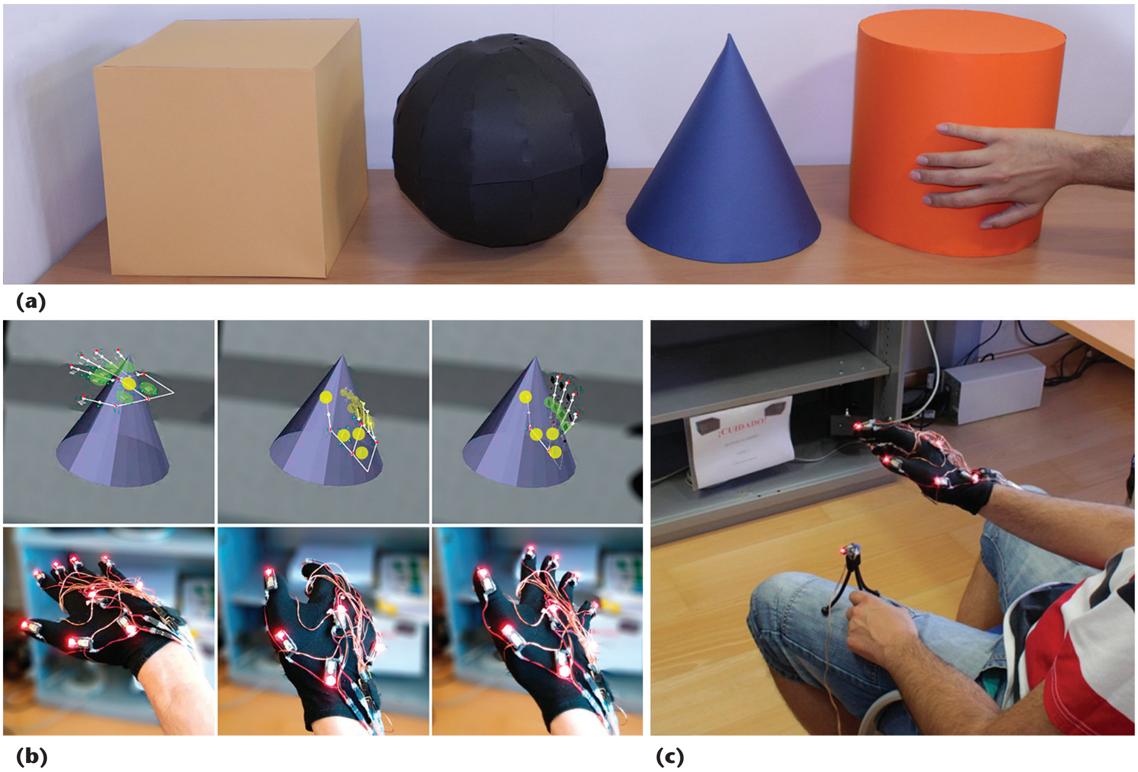


Figure 5. Experimental setup. (a) The four physical paper models used in the experiment. (b) Different palpation movements used to identify the cone, where the different actuators activated are highlighted. (c) One of the users performing the experiment, using the tripod as a reference.

an improvement in the quality of the vibrotactile stimuli. This led us to include the overdrive and active braking techniques in the device.

Lastly, the participants found it difficult to locate the virtual objects in the real world, so we added a small tripod with a tracked LED to give the users a reference point. With this as a reference, they were able to locate the virtual object in the real world and change its location to make the experience more realistic.

Following the first stage of the evaluation, 16 participants took part in the second stage of the experiment—two women and 14 men, with a mean age of 29.1 years (with a standard deviation of 5.9 years). The participants each had a 5-minute training period to acquaint themselves with the shapes and the device. The geometric shapes were explained, and the paper models with the same dimensions and proportions as the virtual ones were given to the participants before the experiment to provide a better understanding of their topological properties and size.

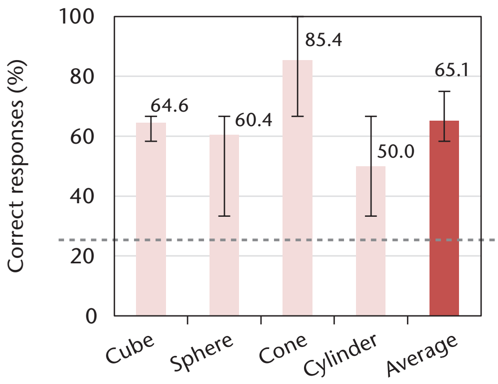
The participants were given the virtual 3D shapes individually (12 objects in three blocks) and asked to identify them as fast and accurately as possible. The order was randomized and no other variables were examined to keep the experiment short. This was because even though the vibration was tuned to produce a gentle feedback, freehand movements when performed for a long time may cause discomfort (also known as the "gorilla arm" problem).

Stimuli

Because touch recognition capabilities are best assessed with familiar 3D objects,[6,7] in this experiment we used simple geometric objects (a cube, sphere, cone, and cylinder) of similar proportions (see Figure 5a). The size of the objects was not included as an independent variable in this study. If, for instance, the cylinder was thinner and longer, it could be distinguished more easily from the rest, but this was not the purpose. Thus, similar proportions added a level of complexity to the identification task.

All the objects had a maximum of 250 mm in all three dimensions, which is large enough to allow the user to explore the object with the whole hand and reach it by simply moving an arm through the air. An excessive size would have made the exploration more difficult. Smaller forms of these objects have also been used in previous experiments with a Phantom device[6,8] and with other specific multipoint contact force-feedback devices.[7]

To give the users a better idea of their topological properties and to help them to define an identification strategy, the physical paper models were constructed with the same dimensions and proportions as the virtual objects (see Figure 5a).



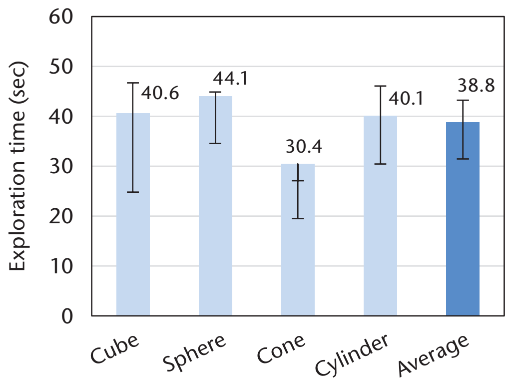


Figure 6. Experimental results for the vibrotactile glove. (a) Correct responses and (b) exploration time. The dashed line indicates the chance level (25 percent). Error bars indicate quartiles 1 and 3.

To localize the 3D shapes, the users had the small tripod as a visual reference of their position in space. Each of the users placed the tripod on his or her right knee (see Figure 5c). Thus, they were able to easily find and center the virtual object.

Results

During the experiment, the test supervisor monitored the participants' exploration techniques. Interestingly, the most common strategy was palpation—that is, moving the hand toward the object's surface from different angles and with different gestures. This technique is less precise than with force-feedback devices, which allow the user to accurately follow the contour of an object.

Figure 6 presents the results of the experiment. Correct responses and times are given for each of the four shapes as well as the average. We included quartiles 1 and 3 to measure the dispersion of the dataset. At first glance, it can be seen that the successful identifications are far above the chance level (25 percent), which is marked with a horizontal dashed line. This indicates that the object recognition task can in general be considered successful.

The analysis of the data indicates a higher success rate in identifying the cone and the shorter time needed to explore it than the other shapes. One possible explanation is that the cone is morphologically different than the others and can thus be identified more easily. In personal interviews after the experiment, the subjects highlighted the relative ease of identifying both the tip and the sloping sides of the cone. They also commented that, as a result of their exploration technique (examining the object from the top down), they tended to confuse the cylinder with the cube.

Further statistical analyses were performed to confirm the different success rates for the different objects. The cone results were tested against the rest of the objects. Given that the data came from a nonnormal distribution and that the same subjects performed all the tests, we used a nonparametric Wilcoxon signed-rank test. The results of the test ($Z = -2.332$, $p = 0.02$) confirmed that the differences observed were statistically significant (95 percent confidence interval), so it can be concluded that, if the objects are different enough, the identification rate is better. The same test was conducted with the cone against each of the other objects separately, and the same results were obtained: cone-sphere ($Z = -2.317$, $p = 0.021$), cone-cylinder ($Z = -2.796$, $p = 0.005$), and cone-cube ($Z = -2.332$, $p = 0.02$). Similar studies were performed for the rest of the figures: cylinder-sphere ($Z = -0.862$, $p = 0.389$), cube-sphere ($Z = -0.362$, $p = 0.717$), and cube-cylinder ($Z = -1.341$, $p = 0.180$). The results showed that there were no statistically significant differences among them, so the differences in the identification rates in Figure 6 are not significant.

Discussion

To compare the proposed device with other haptic devices, we compared our results with those obtained by other research groups in similar evaluations. To our knowledge, only force-feedback devices have so far been used to identify 3D virtual shapes, with one[6,8] or three[7] points of contact associated with different fingers. Their ability to represent surfaces and the highly restricted number of contact points mean that their most common exploratory procedure is contour-following, as opposed to the palpation method used with our device.

Gunnar Jansson summarized a set of experiments performed using a Phantom to identify geometric objects with sizes of 5, 7, 9, 10, 50, and 100 mm.[6] He observed a tendency in which larger objects get a higher percentage of correct judgments and shorter exploration times. Experiments conducted by Maik Stamm and his colleagues also used a Phantom device, although they tested a wider variety of shapes.[8] They used 12 × 12 × 6 mm sizes and, taking into account only the four shapes studied in our experiment, obtained a successful identification rate of 88 percent (calculated from the figures), which is similar to Jansson's success rate. Exploration time was significantly higher (74 seconds), but this could have been because the users had a wider variety of shapes to choose from. Our results are close to Jansson's for the smaller sizes, both in terms of accuracy and exploration time, but they are not as good as those achieved with the bigger sizes.

In another experiment, Antonio Frisoli and his colleagues used a force-feedback device that allows three different contact points associated with the thumb, index, and middle fingers of the right hand.[7] They analyzed the benefits of including multiple contact points in the object shape identification task. To do this, they used geometric objects (a cone, pyramid, hemisphere, and cylinder) and other nonregular objects (a triangular extrusion and pentagon extrusion). They concluded that the participants were able to identify regular objects but found it difficult to recognize more complex and irregular shapes. Thus, although the recognition rate for regular objects was impressive, it should be highlighted that they achieved considerably worse results for more complex objects because the participants' exploration technique was contour-following supported by the force-feedback capabilities of their device, which meant the participants found it difficult to identify the extrusion included in complex objects.

Given these results, the presence or absence of a force-feedback mechanism clearly makes a difference. Even though having multiple points of contact associated with different hand positions (see Figure 2) allows us to use other exploratory procedures, adding enclosure to contour-following, none of these procedures are performed as in natural haptics because there is no force feedback. This means that users must concentrate more on the task when they are using their hands to assess the size of an object or exploring its surface because their hand is moving through the air and nothing prevents them from putting their hands inside the object or even moving through it from one side to the other. This additional concentration requires more exploration time. In addition, the mechanoreceptors stimulated by our vibrotactile device are not the same as the ones that are stimulated in a natural exploration. However, despite these shortcomings, our device achieves a good correct response rate. With longer learning times, users should get used to the new stimuli, so we can expect the exploration times to be shorter.

All in all, the force-feedback devices used in the other experimental studies have several disadvantages that seriously limit their use. As the workspace and the number of contact points increase, so does their complexity and cost, which put them out of reach for mainstream users. Even if users could afford these systems, their workspaces are usually restricted, which limits their freedom of movement and thus prevents the implementation of floating, mid-air interfaces.

The proposed haptic display was tested with a highly demanding task: identifying virtual 3D shapes with no visual feedback. Given the similarities in the shapes and sizes of the objects used in our evaluation and that the lack of force feedback makes the exploratory procedures different from natural haptics, we think that an average identification rate of 65 percent is a remarkable result. This work advances efforts to implement this technology in applications unsuitable for other complex devices. In fact, the identification rate was above 85 percent in the case of the cone, which means that we can obtain better results when the objects being identified are dissimilar.

Based on our analysis of the results, two aspects should be explored in future work. First, we think that a considerable period of time is needed to get used to perceiving shapes through vibrations, so longer identification training times should improve the success rate. Second, we believe including in the evaluation other types of objects, of different sizes and irregular shapes, would improve the identification rate, even beyond that of force-feedback devices.

Finally, it should be noted that this work only covers the shape of virtual 3D objects, but we have previously studied the identification of textures[2] and are currently evaluating other haptic features, such as weight. Our goal is to evaluate all the exploration procedures proposed by Lederman and Klatzky[1] to explore the potential of this technology. Our results so far give us confidence that our haptic display will be useful in many environments that require object recognition or support for peripheral vision. Of special importance are the new interfaces that go beyond the screen, in which users are simply swiping the air with their hands. In such cases, simulating actual object interaction can enhance the user's experience and productivity.

Acknowledgments

This research was partially supported by a grant from the Regional Government of Castilla–La Mancha, Spain, and the European Social Fund and also by the Spanish projects TIN2012-34003 and DPI2015-65426-R. We thank the participants for taking part in the experiment.

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