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Identification Accuracy and Efficiency of Haptic Virtual Objects Using Force-feedback

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Abstract

In the field of constructive solid geometry, modelers combine (or decombine) geometry primitives like cones, cylinders, prisms, pyramids and spheres to create digital models of physical items. Haptically recognizing the shape of such complex models in virtual environments represents a challenging task if just minimal information is conveyed while using force-feedback with a single point of contact. However conducting object identification experiments is very important for determining chances and limits offered by such a haptic feedback system. Therefore this paper describes two experiments using planes and surfaces based on geometry primitives, geometry primitives themselves, frustums and combined geometry primitives for recognition task. In the first experiment the models are postured upright (not rotated). In the second experiment the same models are randomly rotated to investigate influences of posture. Test persons' averaged identification accuracy and exploration time are determined. Furthermore important statements and sources of identification errors are listed that have to be considered to allow intuitive, reliable and fast exploration.

Index Terms: haptic, force-feedback, virtual objects, identification, geometry, shape

1. Introduction

If we want to create realistic and immersive virtual environments, we have to consider the important role of the human haptic sense. In virtual environments, therefore, haptic feedback is delivered by haptic feedback devices enabling the user to touch, explore, interact with or to manipulate virtual objects. In situations in which no or not sufficient visual information is available, the haptic sense even plays the dominant role. In this case, using a haptic feedback device is crucial and indispensable for gaining information about the virtual environment and the objects in it.

A typical example is that of blind users depending on haptic feedback because of the lack of visual input. They can benefit highly from touchable haptic shapes, forms and objects in virtual environments. So blind persons can haptically learn about mathematical functions [1], can learn by exploring 3D models as substitute for graphics out of books (e.g. in the field of human anatomy and mechanics) or exploring 3D models of museum pieces [2], can play haptic computer games [3] and so on. But also not-visually impaired people directly profit of haptic feedback devices in immersive virtual environments. They can use them, among others, for medical training [4], teaching and learning in general and even for e-commerce [5]. In these cases, haptic feedback is not only useful if virtual objects or parts of them are hidden or not completely visible because of an inconvenient visual representation (e.g. weak light source, imprecise graphical output on screen). On the contrary, collecting haptic and visual information simultaneously is very valuable since the nervous system seems to combine them in a statistically optimal fashion. Through visually investigating and actively haptic exploring virtual 3D objects, details of their properties (like size, weight, shape and surface) can be extracted more precisely than without making use of the sense of touch [6, 7]. Moreover, an increase in memory performance is also achievable [8].

In most examples respectively applications mentioned above haptic feedback devices are used for exploring and identifying virtual shapes, virtual forms or virtual objects. So this task plays an important role. In our daily life we use our hands as powerful tools allowing fast and easy exploration as well as identification of real objects [9, 10, 11]. Because of the numerous, high-specialized cutaneous and kinesthetic receptors in our fingers, thenar eminences and palms, we are able to recognize geometrical properties (such as shape and size) and material properties (such as texture and stiffness) as well as to feel the temperature of the explored object. By collecting and integrating this information, it is possible to build up a mental image and, finally, to identify the object. Scientists like Klatzky, Lederman and Metzger figured out that identification of common objects (e.g. glass, battery, noodle, key) through manual exploration succeeds with almost 100% accuracy and takes only 2-3 seconds [9]. This is because of the diversity of information provided to the whole hand and the diagnostic features of the common objects known from experience.

If we want to obtain similar identification accuracy in virtual environments, we need a haptic device providing cues for geometry, material and temperature. However, the development of such a device is expensive due to technical complexity. Therefore it is scientists' task to find the basic information needed, e.g. for important tasks like virtual form and object identification. With this knowledge, it should be possible to create realistic experience by using less complex and thus cheaper devices.

This paper concentrates on determining test persons' averaged identification accuracy and efficiency of virtual touchable objects varying in properties of shape. The experimental conditions are maximally constrained to determine which basic information has to be delivered for solving the task. After Lederman & Klatzky, minimal information is obtained if real objects are explored with a rigid probe [11]. Adapting this situation for experiments in virtual environments requires to use a haptic force-feedback device enabling the test person to get in contact

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with just one point of the explored object at the same time. For calculating adequate force-feedback while touching and following the contour of the virtual object, we set up an experimental environment with implementations for collision detection and force-response and force-control algorithms.
For detailed information on the experimental environment, please see the following section. The experiments, the selected virtual objects and the groups of subjects are described in section 3. Results are presented in section 4 and, finally, discussed in section 5.

2. Experimental Environment

The experimental environment primarily consists of a haptic force-feedback device, a software interface for device control, a software implementation for the haptic rendering algorithms as well as a scripted Matlab-framework used for automating the experimental procedure. Masking audio signals are reproduced via a pair of closed headphones.

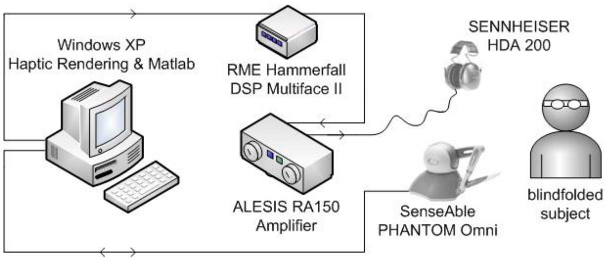


Figure 1: *Experimental setup.*

In the following section, the principle of haptic rendering and the required software implementation is described. Subsequently, the haptic device and its characteristics are introduced.

2.1. Haptic rendering

Haptic rendering denotes the process by which specific cutaneous or kinesthetic sensory stimuli are delivered to the user in order to convey information about a virtual haptic object. This information represents the physical attributes of the object like size and shape (geometry) but also elasticity, texture and so on [12]. Using haptic force-feedback devices in virtual environments requires haptic rendering realized in real-time. Therefore, the following sequence of algorithms, the so-called *haptic loop*, has to be repeated continuously [12, 13]:

- Collision detection:
  The collision detection algorithms are responsible for detecting collisions between objects and the "pointer" controlled by the user (HIP, Haptic Interaction Point). It is determined where, when and in which way collisions (e.g. penetration, indentation) have occurred.
- Force-response:
  The force-response algorithms calculate the interaction force between virtual objects and the HIP when a collision is detected. To create an immersive haptic experience for the user, the resulting force has to coincide as closely as possible with the force that would arise in real world interaction. The calculated values are returned as vectors.
  Furthermore, the interaction force is crucial for the simulation engine to compute their effect on the objects in the virtual environment (see Figure 2).

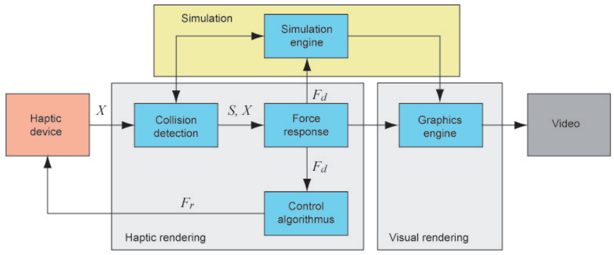


Figure 2: *Haptic (and visual) rendering. Collision detection algorithms detect contacts S between HIP at position X and virtual objects. Force-response algorithms calculate the resulting ideal interaction force F_d. Finally, force-control algorithms adapt F_d to a force F_r in consideration of the capabilities of the device (adapted from [12]).*

- Force-control:
  Due to hardware limitations the forces calculated with the force-response algorithms cannot be applied to the user directly. Therefore, the force-control algorithms are used to adapt the vectors to the capabilities of the device. The arising error between ideal and applicable forces is thereby held minimal.

In comparison to graphics, haptic rendering is an extremely demanding computational process. For maintaining a stable system that imposes smooth and realistic forces on the user, update rates of 1 kHz are needed [14]. Developing and implementing such a virtual environment with haptic touch feedback is a complex and multi-annual work. Today there are several open source haptic frameworks available for academic research providing the mentioned algorithms for haptic rendering (e.g. Chai3D, H3DAPI, OpenHaptics). For our experiments, we used the Chai3D framework developed at the Stanford University, California. For detailed information on the implemented algorithms for collision detection, force-response and force-control, please refer to the documentation [15].

2.2. Haptic force-feedback device

As mentioned in section 1, minimal information is obtained if real objects are explored with a rigid probe. Adapting this situation for experiments in virtual environments requires to use a haptic force-feedback device enabling the test person to get in contact with just one point of the explored object at the same time. Thus, we decided to use the impedance controlled PHANTOM Omni from SensAble technologies providing 6 dof (degrees-of-freedom) positional sensing and 3 dof force-feedback. This small and desk-grounded device consists of a robot arm with three revolute joints. Each of them is connected to a computer-controlled electric DC motor. When interacting with the device the user holds a stylus that is attached to the tip of the robot arm. This stylus represents a rigid probe exerting a force at its tip if appropriate voltages are sent to the motors.
The technical specifications for the PHANTOM Omni haptic device are outlined in Table 1. A complete overview can be found in [16].

3. Experiments

Looking at the daily-used objects surrounding us (e.g. on the desk at work or in the kitchen at home), we quickly recognize

Table 1: *PHANTOM Omni Technical Specification.*

Force feedback workspace	$>$ 160 W x 120 H x 70 D mm
Nominal position resolution	$>$ 450 dpi (0.055 mm)
Maximal exertable force	3.3 N
Continuous exertable force	$>$ 0.88 N
Stiffness	X axis $>$ 1.26 N / mm Y axis $>$ 2.31 N / mm Z axis $>$ 1.02 N / mm
Backdrive friction	$>$ 0.26 N

that these objects are widely differing in shape and size. However, considering a small degree of simplification, all of these objects can be built up of geometry primitives like cuboids, cones, cylinders, prisms, pyramids and spheres. In the field of constructive solid geometry, modelers cleverly combine (or decombine) these geometry primitives in order to create digital models of physical objects. Haptically recognizing such complex models represents a challenging task if just minimal information is conveyed while using force-feedback with a single point of contact. However, conducting a shape respectively object recognition experiment with simplified stimuli (section 3.2) offers great possibilities to determine chances and limits given by basic information and the device.

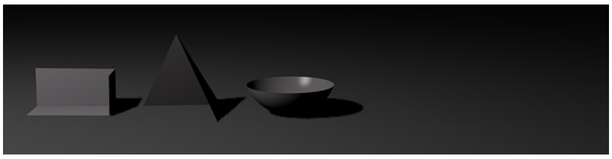
3.1. Subjects

All test persons stated to have no experience in using haptic force-feedback devices. Most of them were students at Dresden University of Technology. The first group consisted of 10 subjects (7 male and 3 female, thereof 1 left-handed) taking part in the first experiment. They were in the age of 20 and 47 (mean 26 years). The second group also consisted of 10 subjects (7 male and 3 female, thereof 2 left-handed). They participated in the second experiment and were aged between 20 and 34 (mean 23 years).

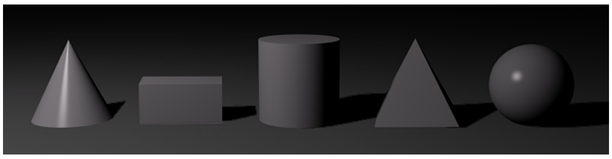
3.2. Stimuli

As mentioned at the beginning of section 3, it is possible to build up objects with high complexity starting from simple ones using geometry primitives. Therefore, in a first step, the identification accuracy of haptic virtual geometry primitives has to be determined (cone, cuboid, cylinder, pyramid and sphere). Going a step further, we modified these primitives by creating frustums. In a third step, two combinations of geometry primitives are chosen for the recognition task. All of the described models are shown in Figure 3b-d. These stimuli do not represent very complicated objects, but they provide different degrees of complexity what is already sufficient to understand how accurate and effective test persons can explore and identify them. Furthermore, it is important to know whether test persons' identification accuracy and efficiency of 3D haptic virtual objects is the same as of haptic virtual planes and surfaces. To get an initial idea if it is more or less difficult, where differences are and what problems occur, we prepared three examples of such stimuli based on geometry primitives (Figure 3a).

Autodesk 3ds Max was used for modeling the stimuli. To arrange with the workspace of the device without difficulty the width, height and depth of the models is limited to maximal values of 12 cm, 12 cm and 6 cm. The models levitate in the center of the virtual scene statically, so it is not possible to move them. Damping is set to zero and their stiffness to maximum.



(a) planes of a cuboid and a pyramid, part of a spherical surface



(b) cone, cuboid, cylinder, pyramid and sphere

(c) frustum of a cone, a cylinder, a pyramid and a sphere

(d) cone and cylinder, cuboid and cube

Figure 3: *Selected haptic virtual objects: (a) planes and surfaces of geometry primitives, (b) geometry primitives, (c) frustums of geometry primitives, (d) combined geometry primitives.*

3.3. Procedure

3.3.1. Training

At the beginning the test person gets introduced to the device, the names of different shapes and to the optimal exploratory procedure (EP) for haptic exploring with a single point of contact solely. This is called *contour-following EP* [11]. Subsequently, the subject passes some training sessions to get familiar with the device, the EP and the task.

3.3.2. Experiments

Experiment 1 After successfully completing the training sessions, the subject puts on headphones reproducing pink noise to mask the sounds generated by the PHANTOM Omni. The subject also gets blindfolded so that recognition performance relies on haptic percepts only. For automating the experimental procedure, Matlab is used:

- The current stimuli (one of the models out of Figure 3) is selected randomly and integrated into the virtual scene.
- The subject gets informed if the model that has to be explored consists out of planes (resp. surfaces) or whether it is a 3D virtual object.
- The virtual scene on screen is filmed for subsequent evaluation during the exploration process.

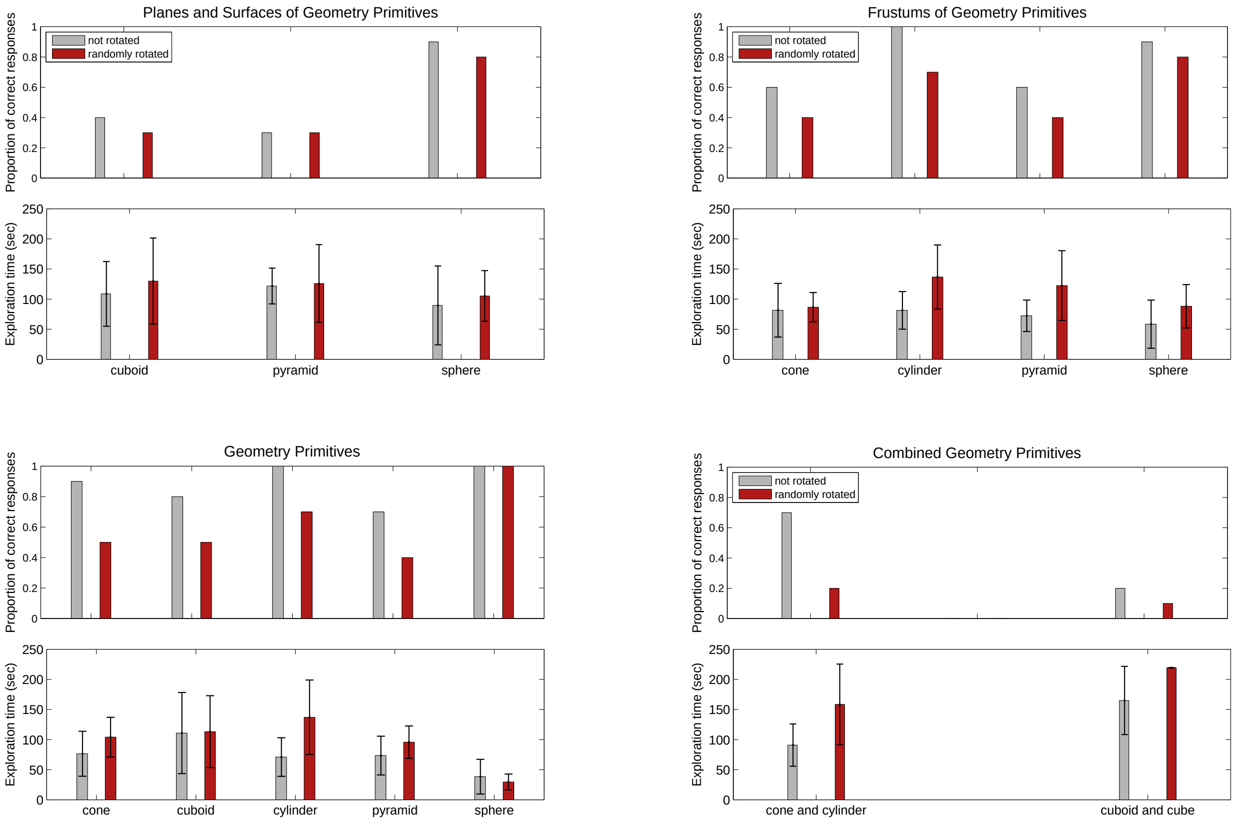


Figure 4: *Proportion of correct identification and mean exploration time needed for correct identification (± standard deviation). The results are shown for not rotated virtual objects (grey bars) as well as for randomly rotated virtual objects (red bars).*

- The required time for solving the task is taken, starting when the first collision is detected and stopping as soon as the subject has identified the object.

- The subject is questioned utilizing a graphical user interface relating its haptic perception. If he/she explored the planes of a cuboid respectively pyramid or the spherical surface, it has to be selected how many planes were present and how they were shaped. If the test person explored a 3D virtual object, he/she has to decide if a solid figure, a frustum or a combination of solid figures was perceived. At the next step it has to be defined what solid figure, frustum or combination of solid figures was perceived. Numerous different possibilities are offered like cone, cube, cuboid, further types of prisms, cylinder, different types of pyramids, sphere and torus. So the list also contains objects that are actually not used as stimuli. The data is processed for subsequent evaluation.

This process is repeated for each of the 14 objects. The subjects get no feedback whether their responses were correct during the experiment.

Experiment 2 The experimental procedure of the second experiment is the same as of the first, however, stimuli are rotated in the 3D virtual scene randomly. By this means, it is possible to determine the influence of posture and orientation on the identification task.

4. Results

The experimental results for identification accuracy and exploration time of not rotated virtual objects are outlined in Figure 4. It becomes obvious that recognition differs between and also within the four categories. However, identifying not rotated geometry primitives offers the best results for successful exploration. Especially primitives with no or few edges and corners can be easily identified, e.g. a sphere, cylinder or a cone. Objects like a cuboid and pyramid feature several edges and corners resulting in slightly lower overall accuracy and an extended exploration time. Similar results could be obtained for not rotated frustums of geometry primitives.
Comparing our results for the identification of geometry primitives to them of Jansson [17] who used a bit smaller sized 3D forms like a cube, sphere, cylinder and cone (10cm as maximum in all three dimensions) shows general accordance in proportion of correct responses but significant differences in exploration time. Jansson determined a proportion of correct judgements of 0.96 and an averaged exploration time of 15 sec. Neglecting the pyramid, we obtain a proportion of correct judgements of 0.93 and an averaged exploration time of 74 sec. The difference in exploration time shows clearly that experimental procedure plays an important role. Subjects participating in our study had to explore all the models very precisely in order to differentiate between solid figures, frustums and combined solid figures in a first step, and, in a second step to label the virtual objects correctly. This procedure was chosen in order to make the task more realistic.

In Jansson's study participants had to decide between four geometry primitives only resulting in faster exploration and decision.
When the task becomes more complex the exploration time needed for correct responding increases again. For correct identification of planes and surfaces an averaged time of 105 sec is needed. This is because subjects had to detect the number of different planes and had to determine their exact shape. Since almost every shape could be selected in the graphical user interface for response (e.g. triangular, quadratic, rectangular, circular and elliptical planes as well as convex and concave curved surfaces), subjects had to explore very precisely in order to exclude incorrect options. Despite time-consuming exploration, recognition accuracy for planes was low (except for the surface of a sphere). Scientists like Kirkpatrick et al. also investigated haptic virtual shape recognition. He conducted an experiment using five smooth-flowing 3D shapes defined by Koenderink and van Doorn [18]. However, the experimental results cannot be compared directly because of differences in experimental procedure and stimuli.
The obtained results for combined geometry primitives are quite different. We determined a proportion of correct responses for the combination of the two well-identifiable geometry primitives cone and cylinder of 0.7, but for the seemingly "complex" combination of cuboid and cube of 0.2 only. Exploration time also varies strongly.

The results for the identification of randomly rotated virtual objects are also outlined in Figure 4. It becomes obvious that altering posture has a strong influence on the exploration task resulting in a decrease of overall identification accuracy and an increase of exploration time required for correct response.

5. Discussion

Conducting such as the described experiments is very important in order to understand which categories of haptic virtual objects can be surely identified and which influencing variables have to be considered if basic information is delivered only. Furthermore, subjects' handling and assessment of the haptic force-feedback device as well as subjects' descriptions of their haptic percepts allow us to determine the limits of certain haptic virtual environments for identification tasks. Knowing these limits is a necessary premise for improving recognition performance of virtual shapes. Therefore important statements, observations and sources of errors gained and revealed during our investigation are alphabetically summarized in the following list:

1. **Corners:**
   The haptic feedback for corners is not acceptable respectively not available. Subjects could not reliably recognize the tip of the explored cone or pyramid as well as corners of the planes.
2. **Edges:**
   A general problem occurs if users try to perceive edges. Virtual edges are haptically touchable, however, subjects often lose track if approaching towards an edge too fast. In this case they have to find the last point of contact for not losing the orientation. This complicates the exploration task considerably. A possible solution is deploying a haptic magnetic effect on the surface of virtual objects in order to prevent losing track [3].
3. **Exploring direction:**
   Subsequent evaluation of the filmed virtual scenes shows that subjects preferably explore in horizontal and vertical directions. However, horizontal and vertical exploring provides not optimal results if the virtual object is randomly rotated in the 3D scene.
4. **Orientation:**
   Some subjects stated to have problems to orientate in the virtual scene. They did not always know where the HIP is located.
5. **Posture:**
   Identifying randomly rotated virtual objects is a very time-consuming and sophisticated task. This is because subjects often need to determine the posture of the different planes and edges of the object before it is possible to integrate them.
6. **Shape of virtual planes:**
   Most of the subjects could not reliably determine the shape of planes (e.g. triangular, rectangular or quadratic). It is not possible to perceive edges and corners in an appropriate way. The exploration process is costly and sophisticated.
7. **Slope:**
   Some subjects stated to have difficulties to differentiate between a cylinder and a frustum of cone. They did not clearly perceive the difference in slope.

One further important fact is that the majority of subjects was insecure in identifying more complex geometrical shapes if relying on haptic percepts only. They stated to have difficulties in solving this complex task and often depended on the method of elimination in decision process or guessing. It also has to be mentioned that a few subjects had less problems to explore particular virtual objects and, thus, required less time for exploration. That is the reason for the variation in standard deviation.

However, all the mentioned facts reduce the usability of a haptic force-feedback device with a single point of contact for identification tasks considerably. Therefore, scientists have to find possibilities to improve the haptic feedback system in order to allow intuitive, reliable and fast exploration in virtual environments for all users. Different fields of research can convey to take up the challenge, e.g. by developing advanced devices, by evolving tricky haptic rendering or object modeling algorithms and so on. Some problems are already addressed but a variety of the leaks listed here could not be solved up to today.

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