STABLE HAPTIC RESPONSE FOR COMPLEX INTERACTIONS

J. Hernantes, D. Borro
CEIT and TECNUN (University of Navarra), Manuel Lardizabal 15, 20018 San Sebastian, Spain

A. García-Alonso
University of Basque Country, Manuel Lardizabal 1, 20018 San Sebastian, Spain

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Abstract: Haptic technology is quite recent and therefore in many cases it is difficult to simulate real contacts or interactions with a high sensation of realism. Collision response methods that calculate the force-feedback tend to cause haptic instabilities when the normal direction changes abruptly. In consequence, collision or contact events are often difficult to render properly in sharp corners by means of haptic devices. This paper describes a collision response method which not only provides users with a stable force feedback, but also a comfortable and convincing haptic interaction. The experimental results show that this approach leads to a smoother force evolution which manages to avoid discontinuities and enhances the quality in the interaction with corners.

1 INTRODUCTION

Humans are able to perceive the environment using all their senses. Usually sight is the predominant sense, although some of the other senses are also needed to perform most tasks. Sometimes, it is necessary to perceive the environment in more detail and all our senses are unconsciously used to obtain the information we need. For instance, maintainability studies need accessibility tests to verify whether each part of the mock-up -static object- is accessible or not. Obviously, a visual test is not enough to detect possible inaccessible parts or manipulate different parts of a virtual model in order to complete an assessment task.

Providing users with the natural ability to use all their senses in a simulation environment is an important goal in the Virtual Reality research area. Within this context, haptic devices are used to provide us with force feedback in domains where it is needed, considerably enhancing interactivity.

Following with the example of virtual simulation of maintainability tasks, an operator moves a virtual tool or mobile object such as a screwdriver using the haptic device, and collides with the different parts that constitute an engine. The haptic forces restored in the collision event should make the operator feel the virtual objects like real rigid objects, and prevent any interpenetration with the environment.

This paper focuses on the problems that virtual corners cause in haptic interactions, in which the force direction changes suddenly causing instabilities in the haptic system. The proposed algorithm manages a proper resultant penetration and normal direction of the collision. In addition to stability and time performance, we have paid particular attention to provide users with a comfortable algorithm to interact with.

Some experiments have been performed to analyze the quality of the proposed method using a haptic device called LHIfAM (Savall et al., 2004), which only provides force feedback in three translational degrees of freedom. However, it can be used with any commercial haptic device. The results show that this algorithm avoids abrupt changes in the computed haptic force obtaining a more continuous force. As a result, haptic stability is improved in complex intersection of surfaces.

The article is organized as follows. Firstly, we present the state of the art of the collision response methods. Section 3 describes the specific problem involving the computation of force feedback. After that, the description of the proposed collision response algorithm is presented in Section 4. Section

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5 discusses the effectiveness of our algorithm analyzing the experimental results. And finally, Section 6 summarizes the results and points out direction for future research.

2 PREVIOUS WORK

There are several approaches which compute force interaction for virtual objects in collision represented by triangular meshes. The existing techniques for haptic rendering with force display can be distinguished based on the way the mobile object used to interact with the environment is modelled: point, ray or 3D object (Basdogan and Srinivasan, 2002).

In point-based haptic interactions only the end-point of the haptic device, known as the haptic interface point (HIP), interacts with virtual objects (Massie and Salisbury, 1994). Zilles et al. (Zilles and Salisbury, 1995) proposed an idealized representation of the haptic device called *god-object*, that is constrained on the surface. Ruspini et al. (Ruspini et al., 1997) use an approach similar to the god-object method called *virtual proxy*. They represent the virtual probe as a small sphere instead of using a point-size god-object in order to avoid falling through the holes in the model, consequence of an inaccurate tessellation. They also proposed methods to smooth the object surface and added friction. Recently, a generalization of the god-object method for six degree of freedom has been proposed providing a high quality haptic display (Ortega et al., 2006).

In ray-based interactions, the virtual probe is modelled as a line-segment and the collision points are computed as the intersection points between the ray segment and the surface of the object. This representation allows users to touch multiple objects simultaneously providing forces as well as torques (Ho et al., 2000). Some works have shown the advantages of this technique in medicine applications like minimally invasive surgeries since the probe is considered a good approximation of long medical tools (Basdogan et al., 2004).

Nevertheless, there are some applications where the point and ray-based methods are not accurate enough since the working tool has such a complex geometry that cannot be modelled using only line segments. In these cases, it is necessary to use the complete 3D model of the virtual tool although its computational cost is more expensive.

Maintainability simulations are an example of applications in which it is necessary to know accurately the forces and torques that prevent users from interpenetrating the virtual mock-ups. Researchers from Boeing (McNeely et al., 1999) have developed a voxel–based method where the mobile objects are represented by a set of surface point samples called Points Shell. They achieve an acceptable performance for maintenance and assembly task simulations. In their later works (Renz et al., 2001, Wan and McNeely, 2003, McNeely et al., 2006), they have presented some improvements that enhance the performance and the haptic stability.

Most haptic rendering methods do not attempt to prevent the interpenetration between the virtual objects, and compute normal forces from the weighted average of penetration depths. Kim et al. (Kim et al., 2003) group the contacts based on their proximity in the 3D space, considering the most penetrating point as the contact point. However, these contact points can be generated and afterwards disappear causing that normal forces change non-continuously. Hasegawa et al. (Hasegawa and Sato, 2004) solve this problem using a spring-damper model on the entire area of contact, which creates a continuous change of normal forces. On the other hand, Otaduy et al. (Otaduy and Lin, 2003, Otaduy and Lin, 2005) create multiresolution representations where geometric details of models are filtered when they cannot be perceived by the user, speeding up in this way the contact query computation for haptic rendering. However, these methods are only valid for convex objects, thus it is necessary to perform a pre-process stage where all the complex objects are simplified into convex pieces. The method presented in this paper can also handle non-convex objects without modifying the original mesh.

3 PROBLEM DESCRIPTION

The process of computing and generating forces in response to user interactions with virtual objects is known as *haptic rendering* (Salisbury et al., 1995). Three main modules can be identified in a typical haptic rendering algorithm: collision detection, collision response and control modules. This paper focuses specifically on the second module. Previous works dealt with the voxel-based collision detection approach (Borro et al., 2004) and the algorithms of the control module (Garcia-Alonso et al., 2005).

A complete haptic rendering sequence could be described as follows: firstly, the control module acquires the position and orientation of the haptic device and sends it to the collision detection module.

With this information, this module checks for collisions between the mobile object and the environment. If there are not collisions, it waits for new information arising from the control module. Otherwise, when a collision event occurs, the contact information is sent to the collision response module which calculates the interaction force. This force approximates the contact forces that would arise during contact between real objects. Finally, the collision response module sends this interaction force to the control module which applies it on the haptic device and maintains a stable behaviour of the system.

There are many methods to calculate the force that must be restored to the user. The proposed method in this article follows the well-known penalty methods in which the force restored to the user is proportional to the penetration inside the static object. It is based on geometry and contact planes which achieves good results not only in computation time but also a nice perception, despite the fact that sometimes the contact points change discontinuously.

4 DESCRIPTION OF COLLISION RESPONSE ALGORITHM

The final haptic response that users feel as consequence of a collision in the virtual environment is determined by a direction and a penetration value. Both factors have substantial influence on users' perception of the final force. This problem becomes more complex when the geometry presents sharp edges which tend to cause haptic instabilities because of the abrupt changes in the normal direction or in the penetration depth.

Figure 1 shows the scheme of the haptic rendering algorithm.

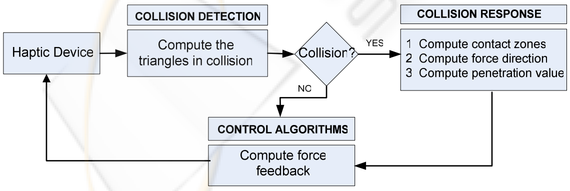


Figure 1: Scheme of the haptic rendering algorithm.

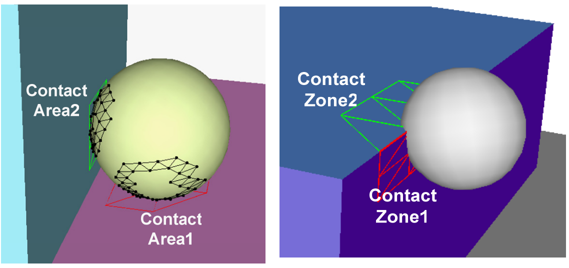
When two objects collide, the group of collided triangles of the static object constitute the "static collision set". The method proposed in this article subdivides this set into areas called "contact areas" in order to compute contact forces. Each triangle in a contact area shares at least one edge with other triangle in its area (see Figure 2a). This division is helpful in order to obtain information about the nature of the geometry in collision, making easier the computation of the final reaction force. Next subsections explain the phases that the proposed collision response algorithm follows for each contact area.

It is well-known that the simulation of non-penetrating rigid body dynamics increases the perceived stiffness of the environment (Srinivasan et al., 1996). In fact, our system does not allow the mobile object to interpenetrate visually into the mock-ups in order to simulate realistic contacts on the objects' surfaces. However, we have decided to disable this option in all figures with the purpose of providing a clearer graphical view of the situations.

4.1 Calculate Contact Zones

In the first phase, the collision response module subdivides the collision area into different contact zones taking into account sharp edges (surface discontinuities). Triangles in a contact zone are connected among them and all the shared edges are smooth. When two triangles share an edge and the angle between the normals to both triangles is lower than a fixed value (crease angle), the edge has a "smooth label".

There will be as many contact zones as necessary to satisfy the smooth connectivity condition (see Figure 2b). Each contact zone approximates a C^1 surface patch.



(a) (b)

Figure 2: Type of contacts. The triangles in red and green represents the colliding triangles of the static model and the black ones belong to the mobile object. Two contact areas, each with two one contact zone (a) and one contact area with two contact zones (b).

For instance, when a collision is detected in a flat surface, all the triangles of the static object in collision will have the same normal vector, and the angle between them will be zero. In that case, there will only be one contact zone. However, when the collision is detected in a corner, there will be different normal vectors in collision. Creating contact zones for these cases, gives information about the nature of the geometry in collision, and it helps to compute a proper force feedback.

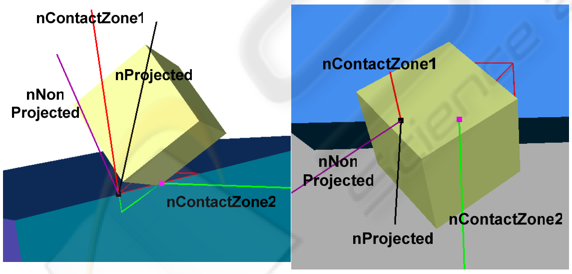
Each contact zone is represented by a zone contact normal that is computed as the vectorial sum of all triangles' normals which belong to that contact zone.

4.2 Area Contact Normal

Adequate contact normals permit providing suitable haptic forces. Three cases can be distinguished depending on the number of computed contact zones.

If no triangles in the contact area share a sharp edge, there is a unique contact zone. In case of rigid and frictionless objects, the reaction force direction is normal to the object surface. Therefore, the solution is trivial since the area contact normal is the zone contact normal.

When a contact area has two or more contact zones, the contact has happened in an area of the static object that is not a continuous surface (a C^0 area). In this case, the area contact normal must be computed in the mobile object. It is because the fact that the normals of static object do not provide enough information to obtain a suitable direction without sudden changes. This is performed using the triangles in the mobile object that collide with the static object. Note that this normal orientation must be reversed.



(a) (b)

Figure 3: Contact state without C^1 in the static model and mobile object (a) and solution for this problem projecting the normal obtained (b).

However, collision situations, where there is not a C^1 contact area in the static object nor in the mobile one, often happen in real applications. These situations often lead to abrupt changes in contact normal in consecutive simulation steps (Figure 3). For the purpose of avoiding these situations, the contact normal is projected on a plane defined by the cross product of the zone contact normals.

4.3 Penetration Depth Computation

Many good algorithms to estimate the penetration value are known (Cameron, 1997, Kim et al., 2003, Redon and Lin, 2006). The penetration depth value is considered as the minimum translational distance required to separate two objects. However, this optimal translation could provide a non useful result, as Figure 4 shows.

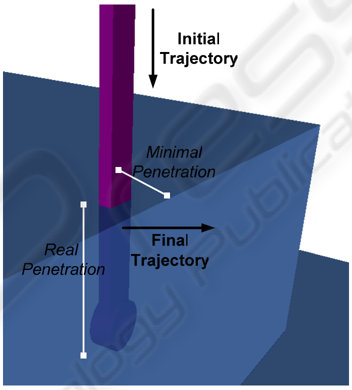


Figure 4: The minimal penetration push away the virtual tool to the right instead of up direction.

Another problem is that in some collision states, triangles from one object are completely inside the other object. When this happens, those triangles do not appear in the list of colliding triangles and further computing should be required.

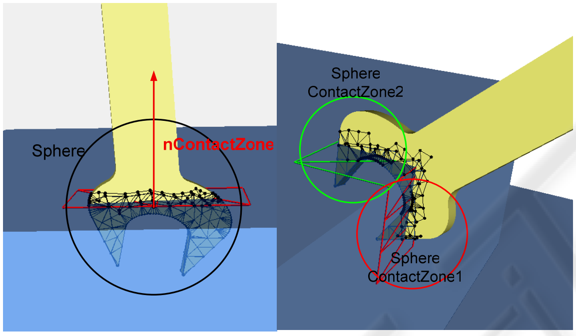
It is supposed that the stiffness of virtual environment would be high enough to avoid large interpenetration of objects. However, high stiff values cause instabilities in the system; therefore a small penetration will be allowed enabling the existence of triangles completely inside the static object.

The proposed method computes a fast approximation of the penetration depth value. It is determined by the distance from the most remote internal vertex to the area contact plane, which is defined by the normal computed in the previous step. The aim is to measure the penetration in the same direction in which the virtual tool will be rejected to the surface.

In order to reduce the computational cost of determining a penetration value, instead of the global geometric problem, a local method based on a bounding volume has been used. Spheres that cover contact zones have been tested. For each contact zone, the centroid is computed in order to place the centre of the sphere and its radius will depend on the area of each contact zone, being large enough to contain all these vertices.

Mobile object vertices (*internal vertices*) that are inside this sphere will be processed to compute the penetration value. The zone contact normal defines two hemi-spheres, one "internal" and the other one "external", referred to the static object. The vertices of the mobile object that are in the internal semi-sphere will be used to compute penetration.

The use of these spheres is not necessarily exact, but simplifies the problem of finding "internal" mobile vertices. We consider that this approximation is specially useful when the mobile objects used to interact with the mock-up are complex, thin and long (Figure 5), such as the tools utilized in maintainability tasks (screwdriver, adjustable spanner…).



(a) (b)

Figure 5: Examples where the use of sphere could be useful since it reduces the vertices to analyze. One contact zone (a) and two contact zones (b).

A point is needed to define completely the area contact plane. When there is only one contact zone, the area contact plane is defined with the centre of the sphere.

If there are more than one contact zone, the set of internal vertices is the union of the internal vertices for each zone. The common vertices among these zones could be used to place the contact plane (Figure 6).

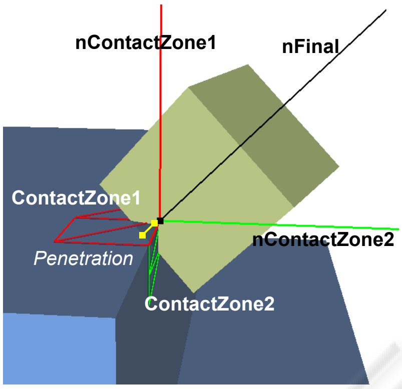


Figure 6: Example of final haptic response: **nFinal** and *penetration* value in yellow. The black point represents the common point between the two contact zones.

5 EXPERIMENTS AND RESULTS

We have implemented our algorithm on a PC running Windows XP operating system with a Pentium Dual Core 6600, 2GB memory and an NVIDIA GeForce 7900 GS. We have developed the algorithm described in this paper and integrated it in a simulation of contact interaction using 3D models with sharp edges.

We rendered the motion of a virtual tool through a convex corner, paying particular attention to the speed rate and quality of force feedback, which are the two of the most important features that a collision response method must fulfil. As explained before, haptic instabilities arise from the delay in the collision detection computation and because of abrupt changes in the haptic force value and direction.

In order to analyze the efficiency of these two aspects, two different types of experiments have been accomplished. The first experiment analyzes the influence of mobile object's tessellation on the penetration computation. On the other hand, the second experiment studies the direction of computed haptic response. We have also analyzed the users' perception for the proposed method.

5.1 Penetration Study

The aim of this experiment is to study the influence of tessellation on the penetration computation. This is an important point for all methods that are based on geometrical approximations. However, it is even more important when a stable and comfortable haptic response is sought. In these cases, it is advisable to prevent large penetration values in order to avoid abrupt changes in the force magnitude, which might inconvenience users.

We have recorded an ideal haptic device trajectory in which a cubic mobile object is covering a convex edge of the virtual scenario consisted of 45.000 triangles. Then, this trajectory is played using the same mobile object but with different tessellation levels.

Figure 7 shows the penetration measured for different tessellations of the virtual tool. The cube has been non-uniformly tessellated using 50, 100, 350, 800 and 2700 triangles, which correspond to 30, 20, 10, 8, and 4 mm triangle edge length average approximately.

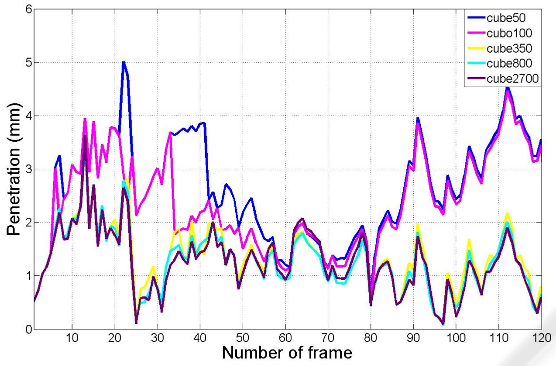


Figure 7: Measured penetration depths using different tessellations for the mobile object.

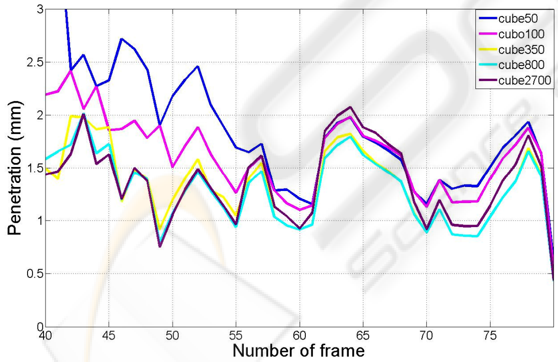


Figure 8: Detail of the previous figure from 40 to 80 frame number.

The results show that coarse tessellations generate important discontinuities since penetration values and the magnitude variation between different frames is larger than using a more detailed tessellation. In addition to this, it can be shown that a too detailed tessellation is not required, as we obtain similar penetration values with the three last levels of tessellation. Figure 8 provides a detail of the graph where this fact can be better visualized.

We have also measured the time performance in terms of the time required to accomplish the different phases of the proposed method (Figure 9). This experiment has been performed without using the spheres which can reduce the number of vertices to analyze in the third phase of the algorithm. The purpose of this experiment is to show that our method achieves good time results, which even could be improved using the bounding volumes.

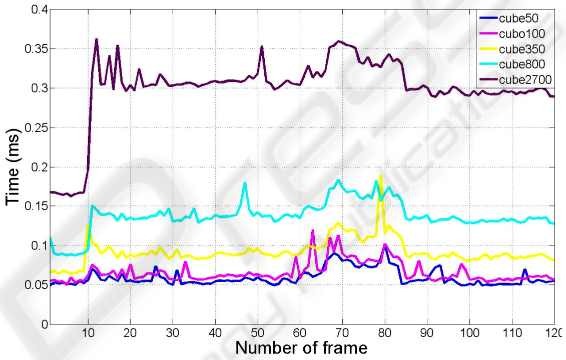


Figure 9: Time spent by the proposed method computing the collision response.

5.2 Force Direction Study

The purpose of this experiment is to measure the quality of the computed force. We can deduce whether the computed force response is valid or not analyzing the direction and module of this force. We consider that sudden changes in the force direction and module can result in force discontinuities or un-stable behaviour, which can produce a defective perception of the collision force. Previous works (Morgenbesser and Srinivasan, 1996) have also studied the influence of abrupt changes in the force direction and how sensitive are humans to these changes.

In this second experiment, it has been simulated the motion of a virtual tool through a convex corner. To be precise, we have used a sphere of radius 50 mm and a fixed penetration of 10 mm. In Figure 10, blue line represents the surface of the convex corner in 2D. On the other hand, red lines are the vectorial representations of the force computed by the collision response methods for each point of the trajectory.

We have compared the results of our proposed collision response method with another method that simply computes a haptic force with an angle of 45º at any corner situation. As it can be noticed in the Figure 10a, the force direction suffers abrupt changes when entering or leaving the corner, producing a defective perception.

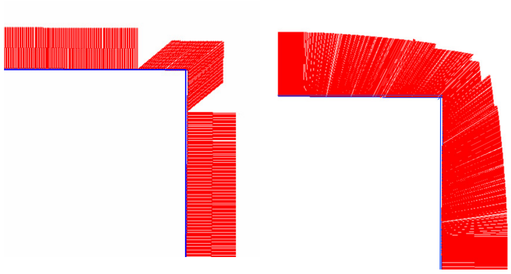

(a) (b)

Figure 10: Force directions in a simulated convex edge using a force response with an angle of 45º (a) and our proposal method (b).

Otherwise, the proposed method provides a progressive change in the force direction (Figure 10b), which avoids instabilities in the final force. In this case, the user can go around feeling a rounded corner, as it happens when we cover a real corner using the finger.

5.3 User Perception

It is quite clear that the method that simply computes forces in corners with an angle of 45º is not feasible because of the instabilities and abrupt forces that it produces.

The method proposed in this paper induces a "rounded corner" feeling to the user, i.e., the user can go around corners and the perceived haptic force changes its direction in a progressive way avoiding sudden changes in the force direction. This method guarantees stability, but the trajectory of the direction of the haptic force is more similar to that when touching a cylindrical object, rather than a sharp corner. In some way, this method imitates a path through a real corner, but touching the corner with one of our fingers instead of a tool. In real world, it is easier to go around a corner with a finger than with a tool like a pen. This is due to the fact that the finger suffers deformation and the contact is physically more stable.

We have made several experiments with different users and they consider that the proposed method is very comfortable to interact with. Although this method does not represent accurately the real physical reactions, users prefer this behaviour.

We also consider that users' perception does not only have a technical factor but also a very important psychological one that could be improved using a multisensory approach to simulate haptic applications. This multisensory concept in haptic interfaces is being studied deeply nowadays. For instance, factors like stereo vision, visually non-penetrating collisions and sound can make the system more immersive (Díaz et al., 2006) and enhance the user perception. In a similar way, some applications should focus more on comfortable haptic interface than in replicating "exact" physical behaviours.

6 CONCLUSIONS

A collision response method that deals with complex collision interactions such sharp edges has been presented. It avoids abrupt changes in the haptic force direction and magnitude, improving in this way overall stability of the haptic system.

The experiments accomplished show that this algorithm generates continuous haptic response in complex collisions. Users also prefer this smooth working environment.

As future work, we are working on enhancing the performance of the system to use it in complex environments and extend it to support future 6-DOF haptic interactions with torques. Moreover, we intend to continue researching solutions to problematic geometrical situations such as peg-in-hole tasks and interaction with thin objects.

REFERENCES

Basdogan, C., De, S., Kim, J., Muniyandi, M., Kim, H. & Srinivasan, M. A. (2004) Haptics in Minimally Invasive Surgical Simulation and Training. IEEE Computer Graphics and Applications, 24, 56-64.

Basdogan, C. & Srinivasan, M. A. (2002) Haptic Rendering in Virtual Environments. IN STANNEY, K. M. (Ed.) Handbook of Virtual Environments: Design, Implementation, and Applications (Human Factors and Ergonomics). London, Lawrence Earlbaum Inc.

Borro, D., García-Alonso, A. & Matey, L. (2004) Approximation of Optimal Voxel Size for Collision Detection in Maintainability Simulations within Massive Virtual Environments. Computer Graphics Forum.

Cameron, S. A. (1997) Enhancing GJK: Computing Minimum and Penetration Distances between Convex Polyhedra. IEEE International Conference on Robotics and Automation (ICRA).

Díaz, I., Hernantes, J., Mansa, I., Lozano, A., Borro, D., Gil, J. J. & Sánchez, E. (2006) Influence of Multisensory Feedback on Haptic Accesibility Tasks. Virtual Reality, Special Issue on Multisensory Interaction in Virtual Environments, 10, 31-40.

Garcia-Alonso, A., Gil, J. J. & Borro, D. (2005) Interfaces for VR Applications Development in Design. Virtual Concept'05. Biarritz, France.

Hasegawa, S. & Sato, M. (2004) Real-time Rigid Body Simulation for Haptic Interactions Based on Contact Volume of Polygonal Objects. Computer Graphics Forum, 23, 529-538.

Ho, C.-H., Basdogan, C. & Srinivasan, M. A. (2000) Ray-based haptic rendering: force and torque interactions between a line probe and 3D objects in virtual environments. 19, 668-683.

Kim, Y. J., Otaduy, M. A., Lin, M. C. & Manocha, D. (2003) Six-Degree-of-Freedom Haptic Rendering Using Incremental and Localized Computations. Presence - Teleoperators and Virtual Environments, Vol 12, 277-295.

Massie, T. H. & Salisbury, J. K. (1994) The PHANTOM Haptic Interface: A Device for Probing Virtual Objects. Winter Annual Meeting, Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. Chicago, IL, ASME.

Mcneely, W. A., Puterbaugh, K. D. & Troy, J. J. (1999) Six Degree-of-Freedom Haptic Rendering Using Voxel Sampling. ACM SIGGRAPH - Computer Graphics. Los Angeles, California, USA.

Mcneely, W. A., Puterbaugh, K. D. & Troy, J. J. (2006) Voxel-Based 6-DOF Haptic Rendering Improvements. Haptics-e, 3.

Morgenbesser, H. B. & Srinivasan, M. A. (1996) Force Shading for Haptic Shape Perception. The International Symposium on Haptic Interfaces for Virtual Environments and Teleoperator Systems.

Ortega, M., Redon, S. & Coquillart, S. (2006) A Six Degree-of- Freedom God-Object Method for Haptic Display of Rigid Bodies. IEEE International Conference on Virtual Reality. Alexandria, Virginia, USA.

Otaduy, M. A. & Lin, M. C. (2003) Sensation Preserving Simplification for Haptic Rendering. SIGGRAPH. San Diego, CA.

Otaduy, M. A. & Lin, M. C. (2005) Stable and Responsive Six-Degree-of-Freedom Haptic Manipulation Using Implicit Integration. World Haptics Conference. Pisa, Italy.

Redon, S. & Lin, M. C. (2006) A Fast Method for Local Penetration Depth Computation. Journal of Graphics Tools (JGT), 11, 37-50.

Renz, M., Preusche, C., Pötke, M., Kriegel, H.-P. & Hirzinger, G. (2001) Stable Haptic Interaction with Virtual Environments Using an Adapted Voxmap-PointShell Algorithm. Eurohaptics. Birmingham, UK.

Ruspini, D. C., Kolarov, K. & Khatib, O. (1997) The Haptic Display of Complex Graphical Environments. SIGGRAPH 97.

Salisbury, K., Brock, D., Massie, T., Swarup, N. & Zilles, C. (1995) Haptic Rendering: Programming Touch Interaction with Virtual Objects. ACM Symposium on Interactive 3D Graphics. Monterey, California, USA.

Savall, J., Borro, D., Amundarain, A., Martin, J., J. Gil, J. & Matey, L. (2004) LHIfAM - Large Haptic Interface for Aeronautics Maintainability. International Conference on Robotics & Automation (audiovisual material). New Orleans, LA, USA, IEEE.

Srinivasan, M. A., G.L, B. & Brock, D. L. (1996) The Impact of Visual Information on the Haptic Perception of Stiffness in Virtual Environments. ASME International Mechanical Engineering Congress and Exposition. Atlanta, USA.

Wan, M. & Mcneely, W. A. (2003) Quasi-Static Approximation for 6 Degrees-of-Freedom Haptic Rendering. IEE Visualization Conference (VIS'03). Seattle, Washington, USA.

Zilles, C. B. & Salisbury, J. K. (1995) A Constraint-based God-object Method For Haptic Display. IEE/RSJ International Conference on Intelligents Robots and Systems, Human Robot Interaction, and Cooperative Robots.