HAPTIC RENDERING OF TRIMMED NURBS MODELS WITHIN AN ACTIVE PROTOTYPING ENVIRONMENT

by

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CHAPTER 2

PREVIOUS WORK

Many researchers have worked toward bringing the full design process into an integrated computer design system. Each stage of the design process has been targeted for research. This section provides an overview of previous work relevant to the presented research. Primarily, work is included that is aimed at enabling a user to use 3D input to perform meaningful work within a virtual environment.

Several groups have investigated the problem of bringing the conceptual stage of design into a 3D environment. Not withstanding Hatvany's [20] claims that it is nearly impossible to sketch CAD designs, work in this area has progressed and the results are becoming more usable.

Others have decided that the ability to store and track early sketches is of more importance than having the sketch be actually in computer form. This approach is actually rather sound since design ideas come to designers at random inspirational moments throughout the day. Therefore, the initial sketches often occur on scraps of paper found at that creative moment. These systems allow the sketches to be scanned into image form and kept with the design throughout the design process.

The modeling stage of design is currently heavily supported with solid CAD systems. Over time, as the power of the computer systems upon which these design environments run has increased, many modeling systems have added support for a variety of input and output devices. However, these are generally for the purposes of visualization, such as the use of a head mounted display, or for passive manipulation, such as 3D trackers for manipulating a collection of models.

The prototyping stage is important to the design process as the results may signify the completion of the design. Problems that are not apparent in the design can often be brought out quickly in the prototype. However, the construction of a physical prototype can be very expensive both in cost and time. The necessity of both cutting costs and bringing products to their fruition more quickly has given rise to the desire for virtual prototypes. There are three main problems to making virtual prototypes a reality. These are the construction of an appropriate virtual environment extension to the design space, development of haptic rendering algorithms that work directly on the designer's model, and the integration of these two components into a single system via distributed computing methods.

2.1 Virtual Environment

An immersive environment permits the designer to enter the design space. This is a powerful addition that allows the designer to view, manipulate, and explore the design using natural and intuitive 3D body motions. The transfer of real world skills into the virtual world in order to make the designer more efficient and reduce training times is a formidable research challenge.

Current CAD systems provide rather basic visual display capabilities but researchers in other disciplines have been working toward creating realistic virtual worlds [32]. The first look into an overlaid virtual world was provided by Sutherland in 1968 with his invention of the first computer graphics driven head-mounted display [63]. The commercial success of such completely immersive systems has been limited to entertainment and simulator purposes, but new applications have been shown to be effective as well.

Architectural walk-throughs [6, 17] have been a success nearly from the beginning. These environments are easy for the user to become immersed within since they represent something familiar to the user. The combination of relatively simple and mostly static geometry with algorithms that prune away geometry that is not visible allows for high display rates.

The Virtual Wind Tunnel was developed by Bryson and Levit in 1991 to allow testing of aircraft aerodynamics [7]. This was an important step in the virtual reality community as it proved to be an effective application even though the computation rate for the simulation was not able to keep up with the display rate.

They have since improved this system to allow it to be extensible for new devices and new visualization tools [8].

Medical applications that allow the surgeon or doctor to see a virtual version of the operating space have also been developed. Augmented displays have been used to show ultrasound images directly on a patient during ultrasound-guided needle biopsies [60]. Some researchers have worked on constructing virtual environments out of helical CT scan data to allow a doctor to fly through a patients colon in pre-surgical exams and surgery planning procedures [25].

Much of the virtual environment research has dealt with user interaction methods for manipulating items within the environment. There are two basic components to this problem: selection and manipulation. The different techniques developed make various trade-offs to meet these goals. Laser beam techniques [39] provide superior selection but suffer from poor manipulation capabilities. Arm-extension techniques such as Go-Go arms [49] provide intuitive hand-centered manipulation but imprecise selection. The worlds in miniature approach [46, 62] provides both easy selection and manipulation but the usability of this method may degrade as the environment size and number of objects increases. Image plane techniques [47] allow hand centered manipulation and simple pointing selection, however arm fatigue, eye dominance, and the hand obscuring objects all limit this approach. Only recently has the sense of touch been considered feasible as an additional channel of input for virtual environments.

2.2 Haptic Rendering

The goal of a haptic rendering system is to produce a sense of contact with a virtual model. This is accomplished by generating forces that can be applied to the user's hand or arm via a haptic device. These forces, called restoring forces, prevent penetration into the virtual model and are calculated using a wall model. There are two basic types of response models, compliance and stiffness, with the stiffness model being most prevalent in haptic rendering systems. Wall models based on the stiffness model often have a restoring force proportional to the penetration depth

[11] and in the direction of the closest point's surface normal. In order to maintain the stiffness of the virtual surface, the force servo loop must run at several hundred *Hz* [40]. This high update rate limits the complexity of the algorithms that can be used to find the closest point and has also restricted the types of models that can be rendered.

Zilles and Salisbury have traced polygonal models using a constraint-based system that tracks a point on the polyhedrons surface [68]. They calculate the penetration depth and surface normal from the tracked surface point. In order to portray sculptured models, they recommend interpolating the surface normals (much like Phong shading in graphics). Systems of this type are often limited to relatively simple models since too much processing time is required for complex models with a high polygon count. Ruspini et al. have extended this work to handle larger polygon counts as well as permit more general graphics primitives, such as points and lines, to be traced by a dimensioned probe [54].

Adachi et al. [2] and Mark et al. [36] advocate the use of intermediate representations to simplify haptic rendering of sculptured models. Stewart [61] also demonstrated this approach by applying a globally convergent numerical method to the system of equations describing the orthogonal projection onto a spline surface. These systems haptically render the model by using relatively slowly changing planar approximations to the virtual model. This method allows more complex models to be rendered but is limited when trying to approximate surfaces with high curvature. Further, since the planar approximations are sampled in time and not by position, the surface felt by the user is not necessarily repeatable during multiple tracings.

Free-form surfaces have been traced by Adachi using distribution functions [1] and by Salisbury et al. using implicit surfaces [56]. Both approaches permit quality tracing of smooth surfaces. However, parametric surfaces, such as NURBS, have become the surface representation of choice in CAD. As such, to use these methods requires a conversion from the original model into one of these other representations. This conversion is difficult and often results in models defined by complex numerically unstable high order functions.

Thompson et al. have demonstrated direct haptic rendering of sculptured models constructed from NURBS patches [64]. Parametric surfaces such as NURBS have the advantage of a compact representation, higher order continuity, and exact computation of surface normals which are all useful in complex, realistic virtual environments [59]. This method has been extended to support more complex trimmed NURBS models [66] and to permit the models to be manipulated [65]. Using this method, designers can touch, trace and manipulate a CAD model at interactive rates without the use of an intermediate representation.

Subsequent to the work described here, Johnson and Cohen followed-up upon the results of Thompson et al. by extending direct parametric tracing to include second order surface information [28]. Nelson et al. demostrated surface-to-surface haptic interaction of sculpted models [42]. Patoglu and Gillespie presented a method based on control theory that maintains the extremal distance even with imprecise seed values [45].

Dachille et al. simulated sculpting of surfaces through a physics based approach [13, 14]. This approach allowed the haptic force to act upon a discreatized representation constrained to the NURBS surface representation.

Research has continued using more recently available six degree-of-freedom devices. The additional degrees-of-freedom allow the resulting forces toinclude torques along with translational forces.

Kim et al. have created incremental methods for computing the penetration depth for collections of convex polygonal bodies [33]. The convex decomposition approach was extended by Otaduy and Lin to include perceptual level of detailing [43]. This can accelerate haptic rendering of very large models.

Johnson et al. use spatialized normal cones combined with local decent to facilitate polygonal model-model haptic rendering [30, 31]. This approach prevents penetration by deriving repulsive forces and torques and is therefore suitable for accessibility analysis.

Duan et al. propose a PDE-based surface flow approach [15]. Their work supports both implicit, distance-field based shape modeling, and dynamic, force-based shape design. The work was embedded in an emmersive stereo environment by Hua et al. and extended to support locallized model modification [21].

Rather than use a method based on penetration depth, McNeely et al. at Boeing have created a voxel-based approach [38]. Their system allows for interaction with the voxelized scene by way of a point-sampled model. By creating the voxel boundary they insure valid virtual prototyping.

Perhaps the most glaring absence in this body of work is the ability to readily modify the underlying geometry of the model. Many of the above techniques require significant preprocessing to setup hierarchical bounding structures in order to speed contact detection. Others require a conversion from the design into an alternate form before haptic rendering can begin. Those that use a distributed model approach complicate geometry modification by introducing synchronization issues. This problem must be solved if haptic rendering is to be pervasive to the design process.

2.3 Distributed Computation

In order for a virtual environment to present a realistic and immersive experience to the user the update rate for the visual display must be kept above $20Hz$ [9]. Similarly, a haptic display must have an update rate maintained at hundreds of Hz [40]. Neither display can be allowed to slow the other's update rate and therefore each must be run in a separate process. These processes must maintain a consistent view of the model if the visual and haptic presentations are to produce a realistic, synchronized, portrayal of the tracing experience. This forces a distributed design approach that can, if approached properly, drastically improve the quality of both processes within one system. Previous work approached the distributed design of virtual environments from a slightly different angle. In these prior works the system needed to be segmented since the components were the visual display and an environment simulation. The simulation would often run at much slower rates than the visual display and therefore needed to be placed in its own process. This would permit the visual display to be kept at a high enough update rate.

The Cognitive Coprocessor Architecture was developed at Xerox as a tool for building virtual reality user interfaces [53]. This architecture was designed to support smooth animation and multiple asynchronous interactive agents. This work was based on the Three Agent Model for supervisory control and interactive systems developed by Sheridan [58].

Distribution over multiple workstations to support the interactive rates of virtual reality interfaces is a main goal in the IBM VUE system [4]. This system assigns a workstation to each device including one for each graphics renderer. This distribution of a single process for each device has become more common since 3D devices are currently noisy and therefore require filtering. The more data used in the filter the better it performs. Therefore, a separate process is used to gather the data from the device at device rates and then supply the filtered results to the application upon request.

The Decoupled Simulation Model is included within the MR toolkit and provides low level support for the design of virtual reality environments [57]. This system provides a unified view of a tracker so that the system need not be recompiled in order to support new equipment or a new organization of equipment. A separate process is created for each tracker, the simulation component and for a geometric model component. This distribution is slightly different than the previous systems as it allows for dynamic model geometry adjustment. The geometric model component supplies different versions of the model to the viewer depending on the current view update rate.

Adachi et al. [2] and Mark et al. [36] have both presented distributed systems for haptic environments. The distribution consists of a graphical viewer and a haptic control process. The haptic device supplies its position to the viewer so that a graphical representation of the devices end-effector can be presented for the user. A simple local representation of the geometry is provided to the haptic controller by the graphical process so that it can render an appropriate force for the user.

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