DEVELOPMENT AND APPLICATION OF A VIRTUAL ENVIRONMENT FOR RECONSTRUCTIVE SURGERY

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ABSTRACT

Objective:

This paper details the development and application of a Virtual Environment for Reconstructive Surgery (VERS). It addresses the technical and user-interface challenges in developing such a system and the lessons learned during application of the system in the case of a 17 year-old boy with a severe facial defect arising from the removal of a soft-tissue sarcoma.

Materials and Methods:
Computed tomography (CT) scans were segmented into bone and soft-tissue classifications using traditional and novel algorithms, a surface mesh was generated, and imaging artifacts were removed, yielding a mesh suitable for visualization. This patient-specific mesh was then used in a virtual environment by the surgeons for preoperative visualization of the defect, planning of the surgery, and production of a custom surgical template to aid in repairing the defect.

Results:
This system was successfully used to plan the surgery of the patient and to produce a custom, patient-specific template that was used to harvest bone from a donor site in order to reconstruct the defect.

Conclusion:
Despite technical challenges, virtual-environment surgical planning is useful as a clinical tool for preoperative visualization, cephalometric analysis, and surgical intervention. It can provide a more precise surgical result than would otherwise be realized using traditional methods.

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INTRODUCTION

Computer-based surgical planning has been investigated by many researchers over the past decade. The promise of the technology is to provide better surgical results with fewer procedures, decreased time in the operating room, lower risk to the patient (increased precision of technique, decreased infection risk), and a lower resulting cost.

The desire to obtain these goals has led to a large number of research projects and clinical applications in this area. Routine use of surgical planning is still in its infancy, although the application of computer-based cephalometric measurement and surgical planning is clearly of great interest to surgeons.

Vannier, Marsh et al [Vannier96] at Washington University in St Louis have done some of the most far-reaching and consistent work in this field. In addition, the orthopedic surgery group [Sutherland94] has also done planning in their area. Also in the United States, surgeons at the University of Texas and Baylor University [Byrd92] have worked on rhinoplasty planning, Johns Hopkins has done orthopedic planning [Chao93], and the excellent orthopedic group at UCLA [Gautsch93] continue to work in this area as well.

Internationally, clinical and engineering groups at the University of Heidelburg [Hassfeld98, Pokrandt96] have done exceptional work in applications of computing and visualization in surgical planning. In addition, the University hospitals at Leuven Belgium [Lamoral90,Verstreken96] have done good work in quantification for maxillar implants.

Researchers at the University College in London [Moss88, Perry98, Ayoub96] have done work in maxillofacial surgery prediction and craniofacial reconstruction. Maxillofacial implant optimization has been researched by the University Hospital Groningen, Netherlands [Rozema92] and other craniofacial visualization has been done at Utrecht University Hospital [Zonneveld89].

In the case of our research, the Virtual Environment for Reconstructive Surgery (VERS) project [Montgomery97,98ab] was started between the NASA Ames Biocomputation Center and the Stanford University Department of Reconstructive Surgery. Its initial aims were to apply the 3D reconstruction and visualization technologies developed for space-related research toward providing surgeons with visualization capabilities to aid in preoperative planning.

The VERS project has since expanded its scope to allow full visualization and interaction between the surgeon and the reconstructed data of their patient [Montgomery99abc]. The result is a complete surgical planning station that allows the surgeon to visualize their patient's data, extract quantitative information (such as distances and angles) directly from their dataset, to actually simulate the surgical procedure for training purposes, and to even generate patient-specific templates that can be used in the surgery.

This paper will briefly discuss the technologies behind this project, detail a case study for which this system proved invaluable, and explore the lessons learned in the production and use of a virtual environment for reconstructive surgery.

METHODS

The system described below consists of four steps. First, a Computed Tomography (CT) scan of the patient was performed. Second, this data was used to segment the bone and soft-tissue of the patient. Third, surface meshes of these tissues were produced from the segmented data and artifacts were removed. Finally, these surface meshes were used for visualization, quantification, and interaction in the process of surgical planning.

Reconstruction

A CT scan of the patient was performed using a GE 9800-class device (General Electric Medical Systems, Waukesha, WI). This data was then transferred from the Stanford Radiology Department to our Onyx InfiniteReality server (Silicon Graphics Inc, Mountain View, CA). Once there, the data was translated (as necessary) from vendor-specific formats into the standard DICOM (ACR/NEMA) format.

In processing the data for a patient, our software would create an intermediate, internal, block-file format of the data. The DICOM image files would be examined, and split into separate directories based on image series and other parameters. Once there, the script would extract the image data from each DICOM image file and build a single, volumetric block file of the imaging data, as well as a separate file comprising all relevant DICOM header information. In this way, rather than parsing each DICOM image file when reading the data into our reconstruction software (~5 minutes of processing), we could instead read the header, then do a very fast block read of the data into memory (~2 seconds).

This block data was read into 3D reconstruction software that had been produced in-house. This software reads and allows us to view the raw CT data, and provides for automated or semiautomated segmentation by voxel classification. In the case of segmenting bone and soft-tissue, a simple thresholding algorithm based on radiographic density (Hounsfeld value) was sufficient for initial segmentation.

However, the resulting segmentation also contains many small features that are not desired in the final reconstruction. These features are due to imaging artifacts, small cavities within the structure of interest, and other anomalies. Therefore, a connected-components algorithm was used to segment out connected voxels into regions. The volume of these regions was then used to select only the major anatomical features, while other regions were omitted from selection. The resulting data provided a volume of segmented data with high specificity.

From this segmented volumetric dataset, a mesh was generated for both the bone and soft-tissue using a Marching Cubes algorithm [Lorensen87]. A number of heuristics were then applied to ensure that the resulting mesh was sufficient for visualization. The resulting high-resolution meshes are then used for preoperative visualization, where great detail is required.

Virtual Environment for Reconstructive Surgery

The Virtual Environment for Reconstructive Surgery consists of the following components:

- Silicon Graphics Onyx InfiniteReality graphics workstation
- FakeSpace Immersive Workbench display system
- Polhemus FasTrak stylus
- StereoGraphics CrystalEyes stereo glasses
- Sense8 WorldToolKit

The WorldToolKit application reads in the given mesh files and allows the user to visualize, measure, interact, and manipulate the data of their patient. This application handles the interaction between the FasTrak stylus 6-degree of freedom electromagnetic tracking/input device manipulated by the user, applies the position and orientation data to a virtual tool in the environment, and provides for real-time stereo display using the CrystalEyes stereo glasses on the

Immersive Workbench.

A number of "virtual tools" were implemented, including:

- Selection/moving tool- allows the user to grab and move/rotate an object
- Marker tool- allows the used to lay down markers on the surface of an object
- Lighting tool- a "spotlight" that allows more precise localization of lighting

Using these tools, the surgeon can apply the selection/moving tool to pick up the skull to rotate it into a new position. By applying the same mechanism, the user could reach into the virtual toolbox to select and then manipulate a new virtual tool. Further, the surgeon can lay down markers on the patient anatomy and have the system compute 3D cephalometric measurements from the marker positions. Finally, other virtual objects, such as spotlights, could be created and moved about to aid in visualization as well.

A number of operations were also available. There were operations for technical feedback such as performance characterization and scene graph display, as well as operations to modify the presentation of objects, such as manipulating object attributes (color, transparency) and turning on/off display of objects. Visualization operations included setting standard viewpoints, rendering modes (wireframe, solid), saving the scenegraph in VRML, and dumping a screen image for later use.

In addition, a number of operations use the locations of the markers. The measure operation measures and displays the distances (linear and surface) and angles between each of the markers. The cut operation subdivides the mesh between to the markers. The reflect operation allows the user to make a duplicate, but reversed object, etc. This marker-based method for interaction proved invaluable in providing quick feedback and interaction with the user.

This system allowed for the visualization, quantification, and, most importantly, interaction with the patient’s data.

RESULTS

This case involves a 17 year-old Hispanic boy [Figure 1]. At age 9 his maxillofacial surgeon found a fast-growing soft tissue tumor located under the boy's left eye. Because it appeared to be an advanced and very aggressive tumor, complete resection was indicated, which required removal of all bone and significant soft tissue on the left side of the boy's face. This aggressive approach was important, as the boy presented cancer-free at age 17, yet required advanced reconstructive surgery. Because this is a particularly unusual and difficult case, we sought to use advanced visualization to aid in the preparation of this surgery.

The boy underwent a CT scan, and his data was processed as outlined above- segmentation, mesh generation, artifact removal, and preparation for visualization. There were 1.5 million polygons comprising the face [Figure 2] and 2.5 million polygons in the skull model [Figure 3]. For preoperative visualization, we typically view these images in stereo, so we require a minimum of 8 million polygons per frame. With technology available at the time, this much information could not be rendered in real-time.

Therefore, the meshes were reduced for interactive visualization purposes in the VERS environment. In the case of this dataset, both the skull and face were reduced to roughly 500,000 polygons for interactive visualization. Our mesh reduction techniques preserve as much detail as possible, while reducing the number of triangles required to represent the surface. However, this was the minimum size that was judged by the surgeons that still provided sufficient detail.

For this case, the surgeons first visualized the high-resolution data of the patient and produced color prints from various views. Next, the VERS system was used to allow the surgeon to interact with the meshes representing the skull and the soft tissue (face). When concentrating on the skull, the rendering of the face can be turned off. The skull could be moved closer into a clipping plane to allow viewing inside the skull for interior structural anomalies. Users could lay down markers on the surface of the skull to measure distances and angles to compare the intact side of the face with the affected side. They also could use the cut operator to cut the bone on the intact side of the face, use the reflect operation to produce a mirror duplicate, and examine the fit of this new piece of bone into the area of the defect. If correct, the resulting surgical template could be written out as a VRML file for later use.

In the case of this patient, the intact side of the face was reflected over the affected side [Figures 4-5] and a template to fix the defect was produced [Figures 6]. This template was then subdivided into more-or-less planar subpieces [Figure 7] using a plane-based cutting tool. Then a CT model of the boy's hip was generated and, within the environment, the pieces of the template could be moved within the model of the hip to find the location of the best curvature match [Figures 8-10]. Then a 2D paper template was produced, traced onto radiological film to withstand sterilization, and taken into the operating room to allow the surgeon to harvest the bone directly from the hip. The film-based template could then be laid onto the donor site (inner table of the iliac crest) so that donor bone of the right size and shape could be delaminated from the pelvis, while preserving its blood supply (deep circumflex iliac artery and vein). While this patient did undergo reconstruction of the bony defect and soft tissues, unfortunately a post-operative image is not currently available due to patient non-compliance with longer-term postoperative care.

By using surgical templates, the surgeons could repair the defect in less time than would otherwise be required. Also, they could repair the defect correctly the first time, without requiring the usual successive procedures for refinement. Both of these benefits also decrease the risk to the patient due to long-term exposure to anesthesia and risk of infection.

DISCUSSION

The major difficulties identified in producing such an environment lie in the desire to maintain high fidelity of the dataset, but to provide a reasonable frame rate for the interactive virtual environment. This is a very different paradigm than occurs in most virtual environment applications. In many application areas, such as architectural walkthrough, many objects may be culled because they are currently out of view of the user. In these cases, a scene graph model is of great benefit to decrease rendering to only those polygons that may be visible in the scene. Also, a bounding box test can be used for aiding in visibility or selection testing. In addition, each object is typically rather small (under a thousand polygons). Finally, maintaining multiple levels of detail of an object can further decrease rendering requirements. These techniques can allow the elimination of the consideration of many objects in the scene and further increase display and selection speed.

In a surgical application, there is typically one, very high-resolution object to be viewed. All of the object is in view, all of the time. Even at 500,000 polygons and with a high-end graphics supercomputer providing a theoretical peak of 10,000,000 polygons/second, we have a theoretical maximum framerate of 20 fps. Our observed performance of 4 fps (without display-list objects) or 8 fps (with display-list objects) was considerably less.

A number of techniques were employed to ameliorate this situation. First, the original meshes of millions of polygons need to be reduced dramatically. Curvature-based (chord height) methods (reduce the number of polygons in areas of low curvature) initially appeared straightforward, but these techniques, when applied liberally, produced large faceted (flat) areas, particularly on the forehead. By not constraining the size of the conjoined regions, such areas of low curvature were over decimated. Employing polygon size metrics (eliminate small polygons because they contribute little to the overall visualization) worked well and solved the above problems. However, these techniques, when applied liberally, would tend to erode away sharp edges of the model (such as near the sutures of the skull), since small polygons are often present along such sharp edges. Finally, a technique which allowed user control of the weighting of these two functions allowed us to decrease requirements, but preserve sufficient fidelity. This is clearly an area that warrants further research.

Second, once the original meshes have been decreased in size as much as the surgeons deemed clinically accurate, the issue of how to render these meshes efficiently becomes important. In our case, the large geometry was split up into smaller "slabs". Therefore, the slab comprising the rear of the skull could be viewed in lower resolution using a level-of-detail mechanism. Note that a rear slab can not be completely culled from the scene because there may exist holes in the slabs closer to the user (through the eyes, for instance).

This slab-based approach also dramatically improved prebuild time (time to optimize the geometry for rendering and create display list objects- an $O(n^2)$ operation) from 20 minutes to 2 minutes. When preprocessing required 20 minutes, the system was very difficult to use and to test due to this time delay. After the reduction in time, preprocessing, and hence its great rendering advantages, could be realized.

In addition, this approach allowed for an optimized selection mechanism. When laying down markers, the marker tool casts a ray toward the geometry and displays a surface-hugging cursor at the location that it is hitting. By subdividing the geometry into these slabs, a quick bounding box test could be used to determine which slab the ray was hitting, before the more expensive determination of which polygon was being hit.

A related difficulty arose in the implementation of certain of the operations listed above. When geometries are small (a thousand polygons), a frame rate can be high enough to allow for interactive, simple polygon deletion for cutting (subdividing) a mesh. While this technique provides a less than optimal cut (very ragged cut lines based on the geometry), it is often used and is trivial to implement. A further refinement is to actually calculate the real location of the cut and to subdivide cut polygons on the fly. Again, this technique works well for small geometries, but does not scale well and does not lend itself to use with lower frame rates.

For these reasons, we developed the marker-based cutting method outlined above. By interactively laying down markers, the user can specify the locations of the endpoints of the cut and the more computationally complex cutting algorithm can be invoked after all cut endpoints are specified. This algorithm can take as much as a few seconds with little impact to the user. Moreover, the surgeons found that this mode of interaction fit their paradigm of cutting from point to point well also. This method of deferring the computationally intense tasks until after all interactive parameters are provided and the user is willing to wait is a technique that worked well in practice.

While the system described was usable in this case, more recent work has focused on clinical applications for mandibular reconstruction, wrist fracture diagnosis and treatment planning, and soft-tissue defect planning. As in the case presented here, we have continued to find great utility in surgical templates to increase the precision and decrease the risk in craniofacial surgery. To support these applications, soft-tissue and rigid-body kinematic modeling software has been developed and will form the basis for true preoperative prediction of postoperative outcome. However, the use of volumetric decomposition methods for real-time interaction as described above will continue to make optimal use of limited computing resources.

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FIGURE CAPTIONS

Figure 1. 17 year-old hispanic male with severe facial defect due to aggressive resection of sarcoma.

Figure 2. Surface reconstruction of soft-tissue rendered with transparency (alpha=0.5) over skull model.

Figure 3. Automatically-generated 3D reconstruction computer model showing skull and extent of defect.

Figure 4: Computer-generated template in place on computer model of skull.

Figure 5. Soft-tissue overlay onto projected result with original skull structure and computer-generated template.

Figure 6. 3D template piece of bone in isolation.

Figure 7. Use of a planar cutting tool to break 3D template into relatively planar subpieces.

Figure 8. 3D template subpieces within virtual environment, with computer model of the patient's hip.

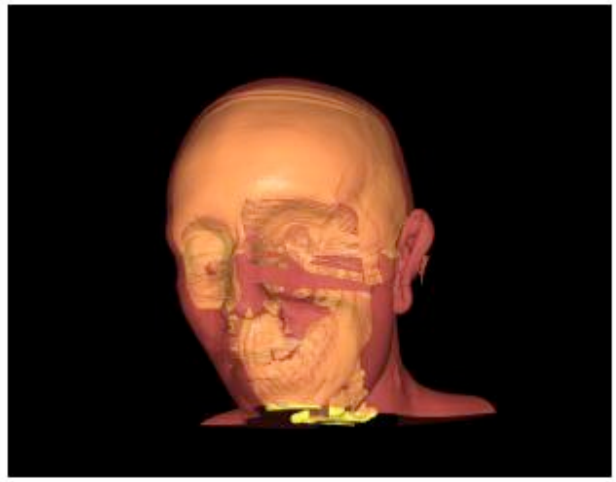
Figure 9. Use of the system to move subpieces within hip model to match curvature.

Figure 10. Extraction of template from hip model.

FIGURES

Figure 1

Figure 2



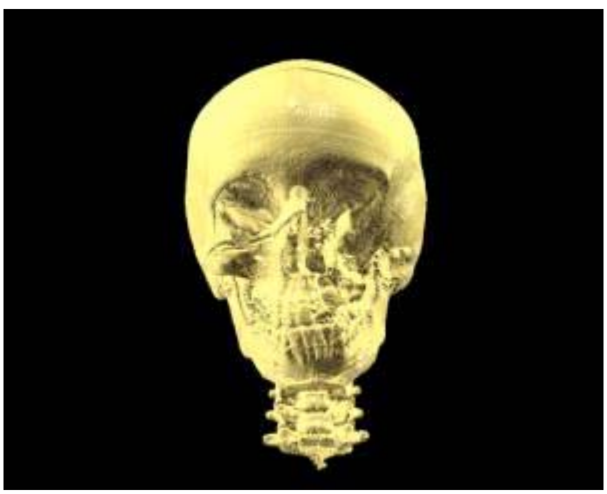
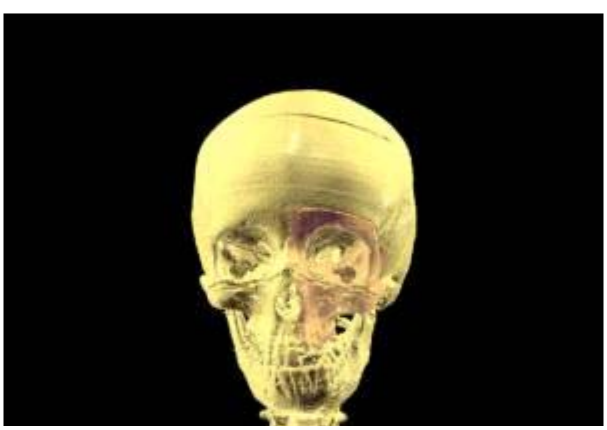


Figure 3

Figure 4



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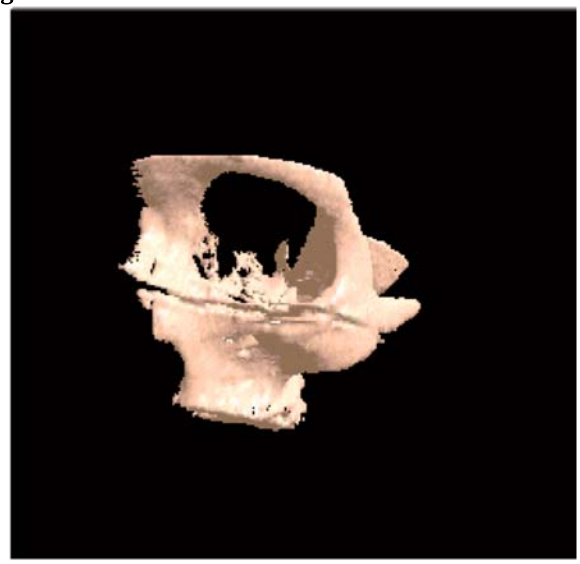

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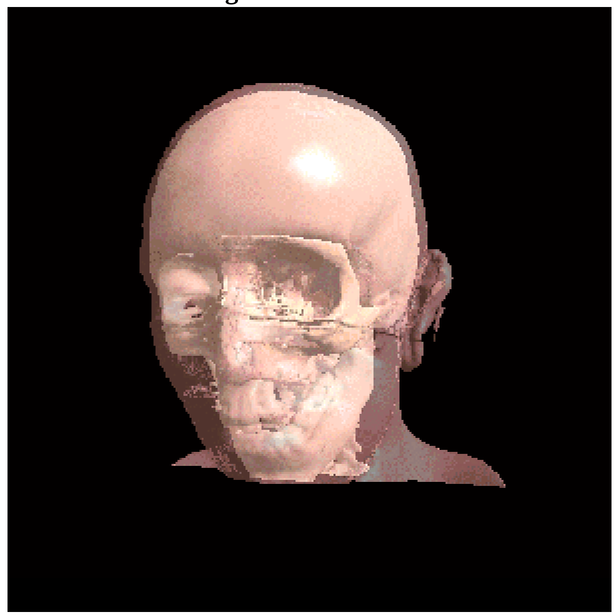

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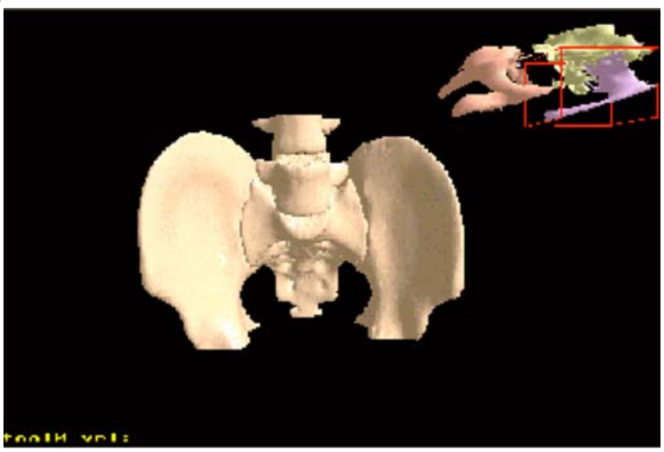

Figure 8

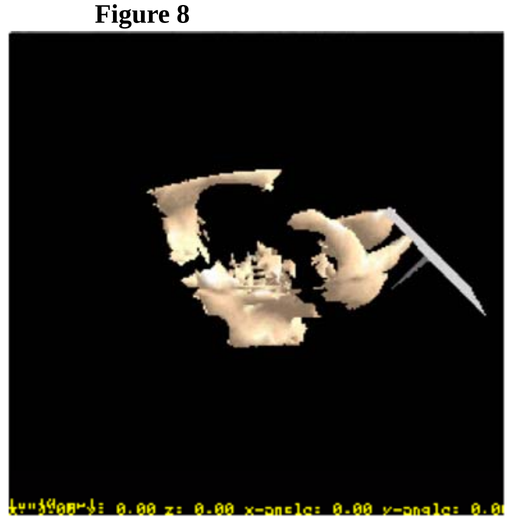

Figure 9

Figure 10