Custom Prosthesis Design, Visualization, and Prototyping*

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Abstract

The design of a custom hip implant can be broken up into several distinct phases which can be carried out by separate toolkits which specialize in the service needed for each stage. We describe a client-server environment in which multiple experts can collaborate in the implant design process and shape optimization, while computations for modelling the femur, simulating loading conditions, and visualization of the results are distributed among a heterogeneous network of workstations.

1   Introduction

SHASTRA is a highly extensible, distributed and collaborative geometric design and visualization environment consisting of a growing number of individually powerful and interoperable (client–server) toolkits which support collaborative multimedia design sessions[1]. In the SHASTRA environment multiple users (say, a collaborative engineering design team) interactively create, share, manipulate, simulate, and visualize complex geometric designs over a heterogeneous network of workstations and supercomputers. In this paper we describe how three of the SHASTRA toolkits, SHILP, a solid modeler, VAIDAK, a medical imaging toolkit, and BHAUTIK, a physical analysis toolkit, can be used in the design of custom artificial implants[3, 8, 9].

2   Custom Hip Prosthesis Design

The design of a custom hip prosthesis can be broken up into five stages. First, a model of the femur of the patient is constructed using VAIDAK. Next, an implant is designed with SHILP using the geometric model of the femur as a guide and constraint. Third, simulations are performed using BHAUTIK to determine the feasibility and performance of the design under different loading conditions. The results of the simulations are then presented in an interactive visualization during which the user can probe different locations in the femur to determine the stress on the femur at that point. Finally, shape optimization is performed based on the results of the simulations and visualizations which have been computed. As we will show, each of these stages can be performed using the distributive capabilities of SHASTRA, harnessing the power of networked workstations.

Figure 1: (a) Reconstructing a Solid Model of a Femur using VAIDAK (b) Video Support for Design Confirmation in Model Reconstruction

Modelling the Femur

VAIDAK, the medical imaging and reconstruction toolkit, manipulates medical image volume data. It can be used to construct accurate surface and solid model representations of skeletal and soft tissue structures from CT (Computed Tomography), MRI (Magnetic Resonance Imaging) or LSI (Laser Surface Imaging) data. The right portion of Figure 1 shows the use of a live video window to cross check the topology of a real femur while reconstructing the femur model from CT data in VAIDAK.

Reconstruction of a bone in VAIDAK is done in two steps. First, the user extracts one or more contours of the bone from each slice of CT data. Second, adjacent sets of contours are joined by either a surface or volume triangulation. VAIDAK has two methods for generating the contours of an object. The user can probe the density values in the CT/MRI data to establish a threshold between the density of the concerned object and the surrounding tissue or bone. By setting this threshold, an automatic contour can be generated starting from a user defined seed point. If there is not a well defined border between the object and the surrounding area, edge detection methods may fail. A manual contour mode is provided to allow the user to trace a contour with the mouse. Using a contour browser, contours can be edited after they are initially created. The contour browser allows for interactive insertion, deletion, and modifying of points with respect to the CT slice data. At this stage, each different slice of data is a completely independent problem, and multiple users can collaborate to produce a model of the femur in a short period of time. In applications such as a hip prosthesis design, it is necessary to create both an inner and outer contour of the bone in order to accurately model the cavity in the bone as well as the thickness of the bone at each point. The left portion of Figure 1 shows a slice of CT data and the contours created for that slice, as well as the contours for the entire solid.

Volume Mesh Generation

A volume mesh of the modelled femur is necessary in order to perform a simulation. Generating a volume mesh of the femur is a task left to VAIDAK, because of the special form of the data. The tetrahedralization is based on the assumption that at each level of data, there are a pair of non−intersecting contours, one inside the other. First, the area between each pair of contours is triangulated. This breaks the problem down into a number of smaller problems which can be handled independently on separate workstations. The region
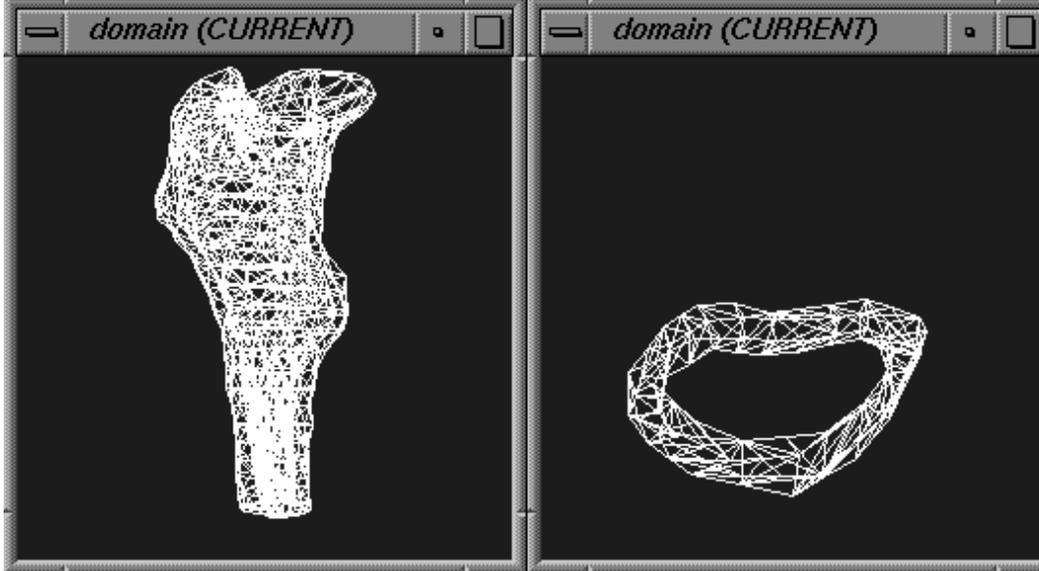
Figure 2: Femur Contours and Tetrahedra Mesh in VAIDAK

between every two cross sections can be triangulated by forming tetrahedra using the triangles formed in the first step. The method for forming the tetrahedralization is based on the surface triangulation of the inner contours as computed by the graph traversal algorithm of Fuchs, Kedem, and Uselton[6]. Since this algorithm produces good triangulations between parallel contours, this will leave the cavity in the femur open. In this extension of the FKU algorithm, each vertex in the graph is a pair of edges, one from the triangulation of the upper contours, and one from the lower contours, three edges joining the endpoints of these two edges to form two triangles. Each edge in the graph corresponds to advancing either the upper or lower edge. When one of these edges advances, the triangles between the upper and lower edges also advance, and the volume between the old and new triangles is filled by tetrahedra. The inner surface of the volume triangulation is made conformal to the triangulation of the FKU algorithm by assigning appropriate weights to the edges of our new graph. If the advance of an edge does not create a new triangle on the inner surface of the femur, the graph edge is given a weight of zero. If the advance of an edge does create a new triangle on the inner surface, the graph edge is weighted according to either the area of the new triangle or the length of the new edge. Details of this algorithm are provided in [2]. As the computations for triangulating the volume between two contours are independent of the adjacent contours, this algorithm allows for distribution by partitioning the contours among a number of workstations. The first step of tetrahedralization, triangulating between the contours, is performed first. For each slice this is an independent task. In the final stage, adjacent contours are distributed along with the computed triangulations, and the computation servers complete the tetrahedralization. Figure 2 shows the tetrahedralization of the femur along with the tetrahedra produced between two of the sets of contours.

Designing an Implant/Modifying the Femur

Using SHILP, we can design an implant (hip prosthesis) based on the femur which was reconstructed in VAIDAK. Designing an implant is simplified by the nature of the contours from which the femoral model was created. Using the inner contours which were created in VAIDAK, contours for the implant can be designed using simple shapes, such as ellipses. At the same time it may be necessary to modify the shape of the femur in order to create good contact regions where stress can distribute easily. The outer contours provide a guide for how much the femur can be altered, as reaming away too much of the femur would leave a thin area in the bone, which would be unsuitable for stress transfer. The task of designing the implant is
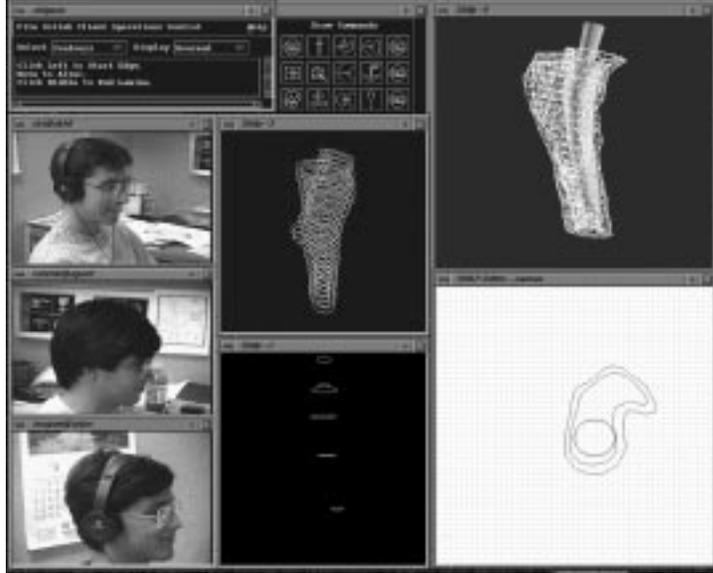
Figure 3: Hip Prosthesis constructed in SHILP in collaboration with VAIDAK and BHAUTIK experts

another task which can be performed easily using the collaborative design and sketching facilities of SHILP. Figure 3 shows a femoral implant constructed in a collaborative SHILP session for the femur pictured in Figure 1.

3 Custom Hip Prototyping based on Physical Analysis

BHAUTIK provides the tools necessary to set up and perform scientific and engineering simulations on geometric models. It allows creation of 2–d and 3–d problems, made up of solids and laminas imported from other systems. Solids are defined in a B-rep (boundary representation) format, and may contain curved edges and faces. Finite element meshes can be generated for each solid. Elements are assigned material properties from a material database. Boundary conditions and forces are imposed on the solid. Results for analysis are obtained through remote calls to any of a number of finite element solvers. These results can then be visualized in BHAUTIK.

Computing Boundary Conditions

BHAUTIK computes boundary conditions based on the contact points between the femur and the implant. The bone may be displaced or reshaped by the insertion of the implant, resulting in regions of contact through which stress would be distributed. Parts of the bone may need to be reamed out for the implant to be inserted. Given a load or net force placed on the implant, it is important to see how that load transfers to the femur. We compute boundary forces on the femur as a proportion of the force on the implant redirected in the direction normal to the plane of contact. In Figure 4, arrows represent forces acting on a part of the femur, resulting from the placement of the implant.

Material Properties

BHAUTIK maintains a material database, detailing properties of various materials such as Young's modulus, Poisson ratio, and density. Materials can be bound to each element in a solid individually, or to regions of a solid specified by the user. Alternatively, for a solid which has been reconstructed from medical data, material properties may be assigned by analysis of the original CT data[5]. The density at any given point
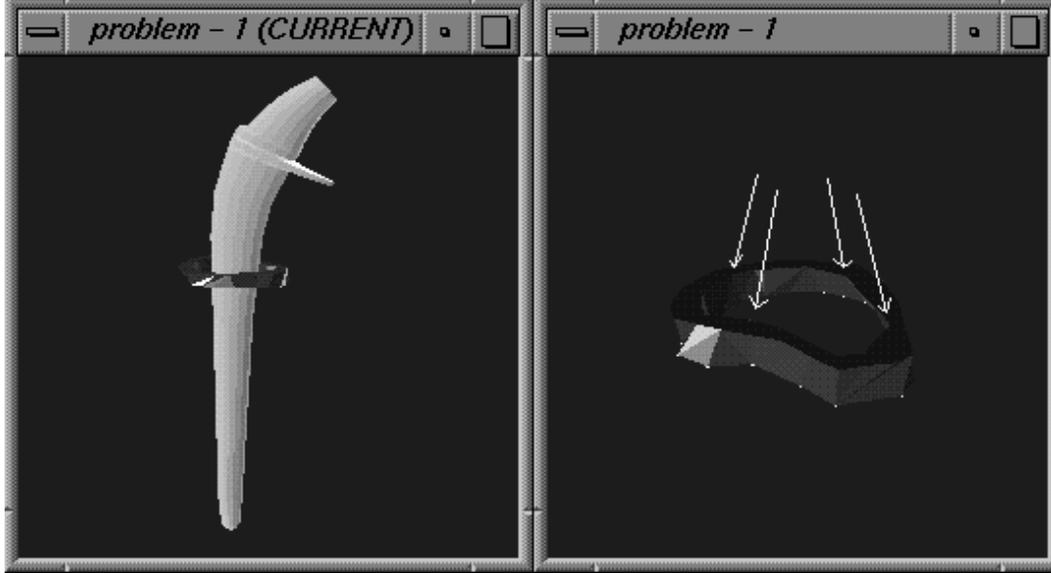
Figure 4: Boundary Conditions Resulting from Prosthesis - Femur Contact

directly corresponds to the CT value in the slice. Other parameters such as elasticity depend on the densities of the surrounding tissue and bone. At this stage we can again use the form of the data to perform this task in a widely distributed manner, assigning groups of elements which contact the same slices to the same processor. Each processor accesses the CT images from which the elements were reconstructed, and obtains average values for the material properties over each finite mesh element. This option permits accurate modeling of bones, emphasizing regions where the bone is weak and subject to harm from additional stress. Using the integration techniques of Bernardini [4], BHAUTIK computes other properties for the solids such as surface area, volume, moments of inertia, and mass.

Visualization

The final stage of a complete analysis is a comprehendible visualization of the results. The method used in BHAUTIK is to map stress values into a colormap, and display each element of the solid based on the average stress over the element. The interior of the solid can be viewed using a cross section mode, in which the user can browse through cross sections of the solid. In figures 5 and 6, the lighter shades on the piece of the femur indicate higher stresses. An alternate method is to display isosurfaces by considering the stress value as the fourth dimension. By constructing C^1 smooth piecewise tri-cubic polynomial functions, we are able to simultaneously interpolate and least-squares approximate the data with a small number of polynomial pieces.

Shape Optimization

Based on the results of analysis, modifications may be made to either the bone or the implant[7]. If a region on the bone is under too much stress, the bone may be reamed out more in that region. If the bone is not thick enough to modify at that point, the implant can be redesigned to redistribute the stress to other areas. Traditional implants vary in the length of the femoral portion of the implant. Changing the length may help to distribute the stress. The orientation of the implant with respect to the femur may also be altered. The SHASTRA collaborative facilities are again used for interaction during this shape optimization phase, as shown in Figure 5.

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Figure 5: Stress Transfer Computation from Prosthesis to Femur in BHAUTIK
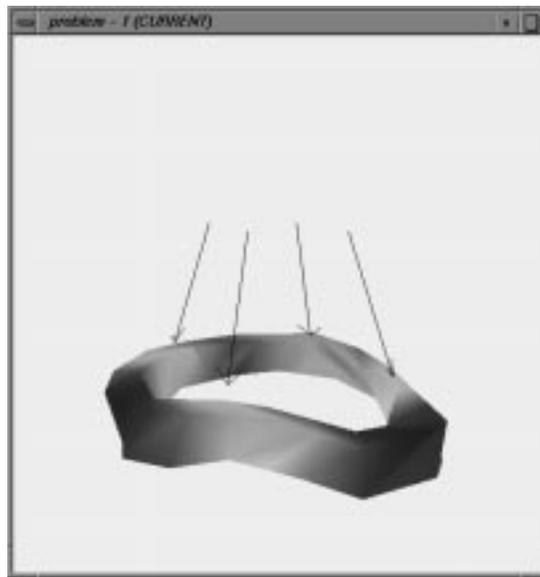
Figure 6: Selective Visualization of the Stress Values after Analysis

4 Conclusions and future work

We have described a distributed and collaborative design system for custom implant design. We begin with model reconstruction using a medical imaging toolkit, and implant design using a solid modeller. Each of these stages is collaborative in nature, allowing multiple experts to participate in the design task. Next a finite element toolkit is used to assign boundary conditions and material specifications to the reconstructed bone for stress analysis. The results are then displayed so that the expert user can determine the suitability of the design. Finally the design can be modified based on the results of analysis. In this environment, several scenarios for modifications of designs exist. Orientation and size of the implant may be changed independently or together to examine the effect of changes. Future plans allow for different materials to be used for implant design to examine the effects of various materials on implant performance.

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