

# Distributed Design of Hip Prostheses with BHAUTIK

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## Keywords

Distributed Systems, Collaborative Design, Problem Solving Environments, Computational Science.

## Abstract

We suggest a procedure for the distributed design of custom artificial implants. The design of a custom 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 the environment which supports this distributed design, and the necessary steps and toolkits to perform the design .

## Introduction

SHASTRA is a highly extensible, distributed and collaborative geometric software environment consisting of a growing number of individually powerful and interoperable (client-server) toolkits which support collaborative 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[4, 10, 11].

## Overview of Bhautik

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 brep 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.

## Domain Creation

The objects manipulated in BHAUTIK are imported from the other SHASTRA toolkits which support solid creation. VAIDAK, the medical imaging and reconstruction toolkit, manipulates medical image volume data. It can be used to construct accurate surface and solid models of skeletal and soft tissue structures from CT (Computed Tomography), MRI (Magnetic Resonance Imaging) or LSI (Laser Surface Imaging) data. Figure 1 shows a femur reconstructed in VAIDAK. The solid modeling toolkit, SHILP, manipulates curved solid objects with piecewise algebraic surfaces. It can be used for the interactive creating and editing of solids with algebraic surface boundaries. Figure 2 shows a femoral implant constructed in SHILP for the femur pictured. Solids constructed in these toolkits can be imported into BHAUTIK for analysis.

## Types of Problems

BHAUTIK supports modeling of several different kinds of physical problems. Problems can be 2- or 3-dimensional in nature. Structural analysis problems model the stress in objects of various composition which are subject to various forces. Heat transfer problems examine the effect of heat sources placed around a solid. Figure 3 shows a BHAUTIK problem session in which a structural analysis is being performed on part of the femur.

## Mesh Creation and Refinement

The creation of good finite element meshes is an integral part of BHAUTIK. Triangular and Quadrilateral meshes are supported in both 2- and 3-dimensions. Good bounded aspect ratio triangulations are supported for both solids and

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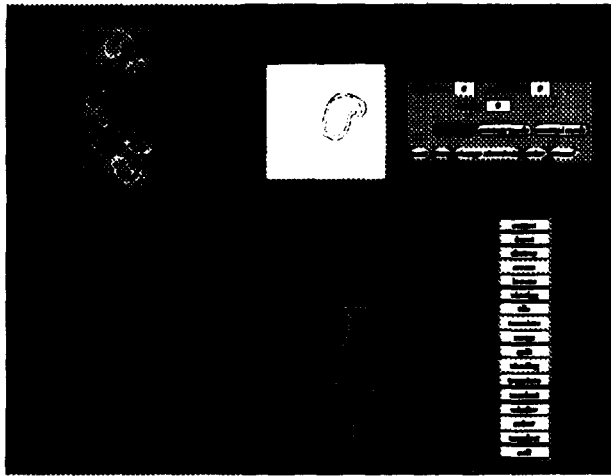


Figure 1: Creating a solid model of a femur using VAIDAK

laminas[2, 7]. Solids can be triangulated by surface or volume triangulation. For greater accuracy in analysis and visualization, meshes can be refined by repeated subdivision.

### 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. 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 [5], BHAUTIK computes other properties for the solids such as surface area, volume, moments of inertia, and mass.

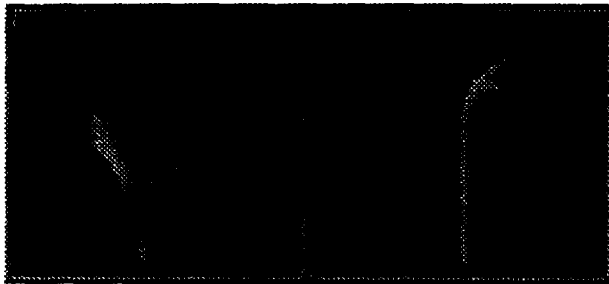


Figure 2: Prosthesis constructed in SHILP

### Boundary Conditions

Solids may be subjected to various boundary conditions. External forces may be placed on particular parts of a solid. Certain nodes may be marked as fixed, or unmovable. Boundary conditions for one solid may also be imposed by the position of and forces on a different solid, to simulate the interaction

between two solids. In Figure 4, arrows represent forces acting on a part of the femur, resulting from the placement of the implant.

### Finite Element Analysis

All aspects of finite element analysis up to this point are independent of the solver which is being used. BHAUTIK provides the capability to interface with a number of finite elements solvers to generate results for problems created by the user.

### Visualization

The final stage of a complete analysis is a comprehensible 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 figure 5, the lighter shades on the piece of the femur indicate higher stresses.

### Hip Prosthesis Design

BHAUTIK and the other related SHASTRA toolkits provide a distributed environment for the interactive design and analysis of a hip prosthesis. VAIDAK accurately reconstructs a solid model of a patient's femoral bone, which SHILP can use as a guide for the design of an artificial hip replacement. Using these two models, BHAUTIK can analyze the interaction of the prosthesis with the original bone of the patient, and provide feedback for possible modifications for the bone and the prosthesis design.

### Creating Contours

To reconstruct a bone in VAIDAK, the user first creates a contour of the bone for each CT/MRI slice. VAIDAK has two methods for creating 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 point. If there is not a well defined border between the object and the surrounding area, methods such as this may fail. A manual contour mode will allow the user to trace a contour with the mouse. After contours have been created they can still be modified using a contour browser, which allows extensive editing of contours. For applications such as a hip prosthesis design, it is necessary to create both an inner and outer contours of the bone, to accurately model the cavity in the bone as well as the thickness of the bone at each point. Figure 3 shows a slice of data and the contours created for that slice, as well as the contours for the entire solid.

### Volume Mesh Generation

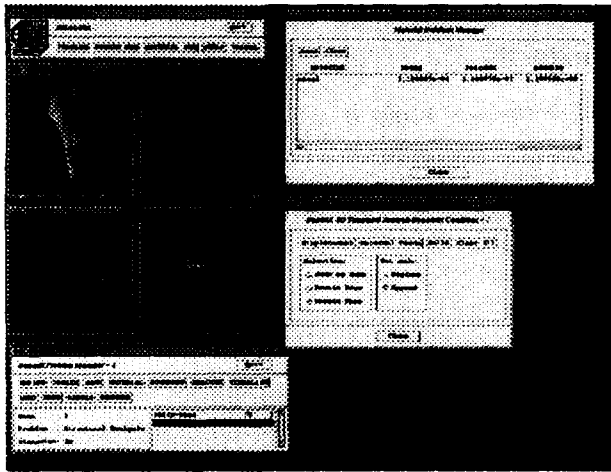


Figure 3: Stress Transfer Modeling from Prosthesis to Femur in BHAUTIK

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. The region between every two cross sections can be triangulated by forming tetrahedron using the triangles formed in the first step. The method for forming the tetrahedron is based on the surface triangulation of the inner contours as computed by the graph traversal algorithm of Fuchs, Kedem, and Useton[8]. 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 end-points 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 [3]. Figure 6 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 based on the femur which was reconstructed in VAIDAK. Designing an implant

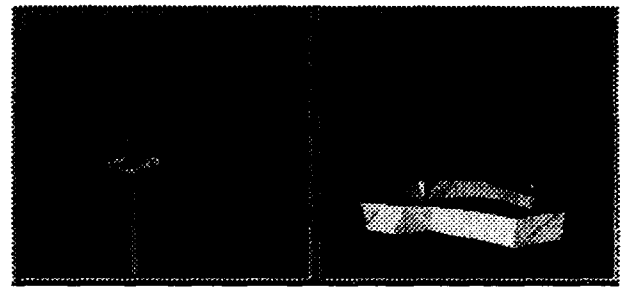


Figure 4: Boundary conditions resulting from contact with another solid

is simplified by the nature of the defined contours in the femur. 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, 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 contours of the implant created in SHILP can be tiled into a solid model of the implant using remote calls to VAIDAK.

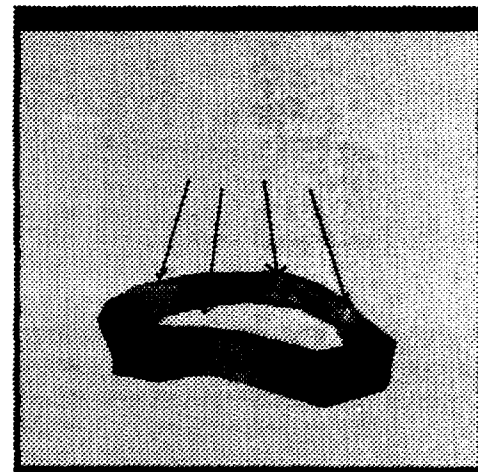


Figure 5: Visualizing the stress values after analysis

#### 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.

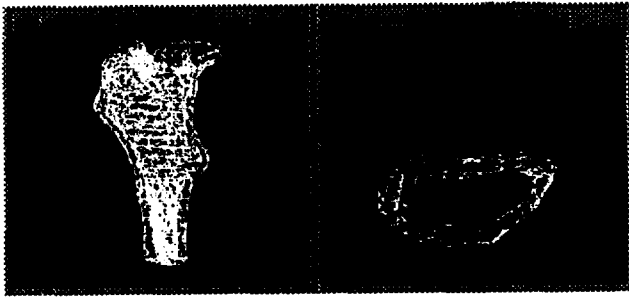


Figure 6: Femur contours and tetrahedral mesh in VAIDAK

### Computing Material Properties

Material properties for solids reconstructed from medical data can be obtained by analysis of the original data[6]. The density at any given point directly corresponds to the value in the CT image. Other parameters such as elasticity depend on the densities of the surrounding tissue and bone. At this stage BHAUTIK reads through the CT images from which a solid was reconstructed, and obtains average values for the material properties over each finite mesh element.

### Shape Optimization

Based on the results of analysis, modifications may be made to either the bone or the implant[9]. 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.

### Conclusions and future work

We have described a distributed design system for custom implant design. We begin with model reconstruction using a medical imaging toolkit, and implant design using a solid modeler. Next a finite element toolkit is used to assign boundary conditions and material specifications to the reconstructed bone for stress analysis. 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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