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# Interactive Product Development and Haptics in Virtual Reality with VrM3d

## Abstract

The VrM3d design tool has been created to investigate the utility of interactive design in virtual reality with force feedback. VrM3d uses two iterative stress approximation methods for reanalyzing part geometry as it is deformed as well as mesh-free analysis to avoid mesh distortion issues, subdivision volume free-form deformation for shape changes, fast collision detection routines, and haptic feedback tied to stress analysis results for shape manipulation. The application runs in virtual reality on a variety of platforms, from desktop computers to the C6 virtual environment at Iowa State University.

## Disciplines

Computer-Aided Engineering and Design | Graphics and Human Computer Interfaces

## Comments

# Interactive Product Development and Haptics in Virtual Reality with VrM3d

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**Abstract:** The VrM3d design tool has been created to investigate the utility of interactive design in virtual reality with force feedback. VrM3d uses two iterative stress approximation methods for reanalyzing part geometry as it is deformed as well as mesh-free analysis to avoid mesh distortion issues, subdivision volume free-form deformation for shape changes, fast collision detection routines, and haptic feedback tied to stress analysis results for shape manipulation. The application runs in virtual reality on a variety of platforms, from desktop computers to the C6 virtual environment at Iowa State University.

**1. Introduction:** The goal of this project is to provide engineering designers with a tool for quick, interactive investigations of many different part shapes early in the product design process. Computer aided design (CAD) geometry, engineering analysis results, and real-time shape manipulation with analysis approximations are combined in a virtual environment with haptic feedback. Working in virtual reality (VR) provides the support for truly interactive design, where users can alter designs quickly while interpreting complex analysis results and evaluating the effects.

To achieve these objectives the VrM3d (virtual reality meshless 3d) application has been created at Iowa State University's Virtual Reality Application Center. This C++ program is based on work from several research projects, combining their results into a software tool for engineering design.

**2. Prior Work:** The research leading up to this project has been ongoing for several years. Yeh and Vance presented a way to perform interactive stress analysis in virtual reality with linear Taylor series approximations based on stress sensitivities [1]. The process, however, was limited by the low accuracy of the stress approximations and the need to identify the design area before the virtual reality interaction could begin.

Later, Ryken and Vance applied this process to a practical engineering problem, the design of a tractor lift arm [2]. The virtual environment made it easy to explore the part design and find a shape that decreased stress concentrations while avoiding interference with the assembly.

To further improve the method, Chipperfield, Yeh and Vance implemented a pre-conditioned conjugate gradient (PCG) re-analysis in addition to the Taylor series approximation to rapidly and accurately compute the resulting stress contours due to shape changes [3]. A reproducing kernel mesh-free method with strain smoothing was added to perform the re-analysis. This analysis method removed the errors induced by finite element mesh distortion as the geometry was changed during the design process.

**3. Application Description:** The current iteration of VrM3d combines several areas including iterative methods for stress approximations, mesh-free finite element analysis, free-form deformation for shape changes, collision detection between deforming models, and haptic feedback tied to stress analysis results for shape manipulation in virtual reality. Figure 1 depicts the VrM3d application in use in VR.

**Figure 1:** VrM3d in the C6 with haptics

**3.1 Iterative re-analysis approach**: First, a model and its boundary conditions is loaded into the virtual world and a full stress analysis is performed. The resulting stress contours are displayed as a color contoured map in the part. As the model shape is altered, a two-stage approximation and reanalysis is performed to re-analyze for an updated stress state so changes may be evaluated quickly.

While the part is being deformed in VR, a first-order Taylor series based on stress sensitivities is used to update the stress contours. These sensitivities are computed through a simple finite difference method based on the original analysis solution. Though it lacks accuracy beyond small geometry changes, the Taylor series is fast enough to update the stress pattern in real time, allowing the designer to see the contour change as the model is altered.

When the user desires more accurate results, or wishes to modify other portions of the model, a pre-conditioned conjugate gradient re-analysis is performed on the meshless model. This method computes a more accurate stress pattern and provides new stress sensitivities for the Taylor approximation.

Factoring and solving the system of equations for the initial analysis and subsequent re-analyses is done with the SuperLU library for solving sparse linear systems [4]. SuperLU is cross-platform, permits a fine control over the factor-solve process, and may be optimized for the computer systemn by building it with the ATLAS libraries.

ATLAS (Automatically Tuned Linear Algebra Software) provides a set of linear algebra routines that are automatically optimized for performance on a particular computer platform when installed [5]. Using ATLAS with SuperLU, as well as in the PCG re-analysis method, helps ensure that the re-analysis runs as fast as possible while maintaining easy portability to other computer platforms.

To further speed the re-analysis process, parallel processing with the Message Passing Interface (MPI) is used when assembling the stiffness matrix for the mesh-free method [6]. MPI allows parallel processing on clusters of smaller PC's as well as larger multiprocessor computers.

**3.2 Mesh-free Analysis Method**: Large changes in part shape and size cause traditional finite element methods (FEM) to suffer greatly from mesh distortion errors without re-meshing. Because reanalysis speed after part deformation is very important, it is desirable to avoid the computationally expensive re-meshing process. Mesh-free methods are similar to traditional FEM, but the displacement approximations are given entirely in terms of the meshless nodes, so no element meshes are necessary [7]. This avoids the mesh distortion issue altogether.

Typically, mesh-free methods have been nearly an order of magnitude slower than traditional finite element methods due to the time required for stiffness matrix assembly. Chen et al. however, have developed a mesh-free method with a strain smoothing stabilization that is comparable in speed to regular FEM [8].

**3.3 Free-form Deformation**: VrM3d uses a type of free form deformation (FFD) referred to as subdivision volume FFD to alter the part geometry virtual reality. The designer first defines a volume around the portion of the geometry to be changed by placing a series of control points in the 3D space surrounding the part. Next, a series of subdivisions are performed on the initial volume to provide a smoother shape. The program then embeds the part geometry in the volume, allowing the shape to be changed by manipulating different control points.

Free form deformation is based on Non-Uniform Rational B-Spline or NURBS modeling [9]. In this work, Catmull-Clark subdivision volumes have been applied as an extension to free-form deformation techniques. This method allows more variety and flexibility in defining the control volume around the part where shape deformations are allowed than standard NURBS-based free form deformation. Figure 2 shows a sample subdivision volume and its control points

**Figure 2:** Sample subdivision volume
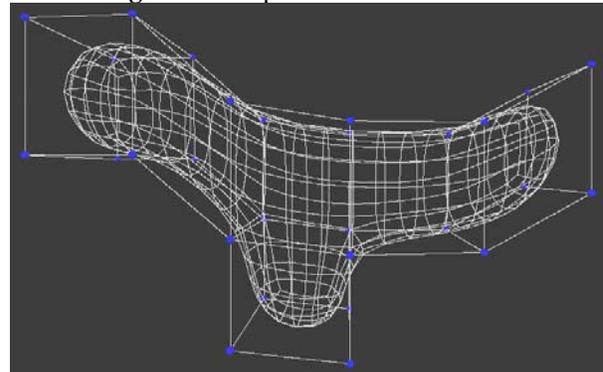


**3.4 Collision Detection**: One of the application areas is in assembly of different parts where detecting collisions between the many models is critical. While most collision detection packages are concerned with many solid models colliding with one another, this research is also concerned with collisions while a model is being deformed. Efficient use of memory is another issue since the analysis of large models can require a substantial portion of the available computer memory. These constraints led to the selection of the OPCODE collision detection package.

OPCODE provides fast collision detection between non-convex polygonal models with a memory footprint many times smaller than similar packages such as SOLID and RAPID [10]. In addition, OPCODE allows the use of deformable polygonal models without rebuilding the collision detection structure, making it a natural choice for this work, since deforming model collision queries are so important.

**3.5 Virtual Reality**: VrM3d is written using the VrJuggler software library developed at the Virtual Reality Applications Center at Iowa State University. VrJuggler provides a framework for programs to run on a wide variety of virtual reality devices, or even a simple non-VR desktop computer [11]. The application's development is targeted for the C6 virtual reality environment. The C6 is a room composed of six projection screens forming the six walls of the room. VrM3d has also been used on a 4-wall PC-based VR system running Linux. A separate computer runs the haptic device, a SensAble Technology's PHANToM, which provides force feedback to a user inside the virtual environment.

**3.6 Haptic Feedback**: In this work, SensAble Technology's PHANToM haptic device is used to provide haptic feedback to the designer while in VR [12]. Since the PHANToM's physical workspace is much smaller than the interior of the virtual environment, say the C6, a mapping was developed to use the phantom over an arbitrarily large portion of the virtual space [13]. The user simply defines a workspace volume around the areas of interest and the program maps the PHANToM physical motion to the virtual space, with a virtual PHANToM endpoint displaying the PHANToM location.

Force feedback is sent to the user when the virtual endpoint is used to grab and move a control point of the FFD volume, deforming the model and changing the stress pattern. By altering the threshold force required to manipulate the control point based on the stress pattern, the user receives additional information about how the stresses are affected by part shape changes that may not immediately be noticeable visually. Haptics can also be used to prevent the user from deforming the part further if a certain value of stress is exceeded.

Since haptic control loops require high update rates (~1000 Hz) for stability, the haptics and PHANToM control are executed on a separate haptic computer, which is networked to the computer(s) driving the VR simulation [14]. Keeping the haptic process separate and communicating via TCP ensures the necessary high update rates, and it allows the PHANToM setup to be portable.

**4. Application Use:** A VrM3d user starts with an initial meshed model, stored in an extensible markup language (XML) format. The mesh is used to position the meshless nodes within the model. Model geometry, mesh, boundary conditions, and material properties are stored in the XML file. Abaqus, a common finite element package, was used to generate these models while a simple file converter creates the XML file from the Abaqus input file. This also makes it easy to use Abaqus to verify some of the meshless method's results for accuracy.

Once the program is running, the model is loaded and the user defines a bounding volume as the allowable deformation area. The application performs an initial stress analysis and sensitivity calculation for selected control points. From there a designer can use the PHANToM to modify the model, select different control points, change bounding volumes, and explore the shape change effects on the part in question. VrM3d has the option to display different contours based on Von Mises stress, maximum shear, etc. as in a standard finite element software package. Multiple models may be loaded into the environment, properly positioned, and each analyzed in turn. Collision detection may be turned on or off as needed. Figure 3 provides a diagram of the program operation.

**Figure 3:** VrM3d operation flowchart
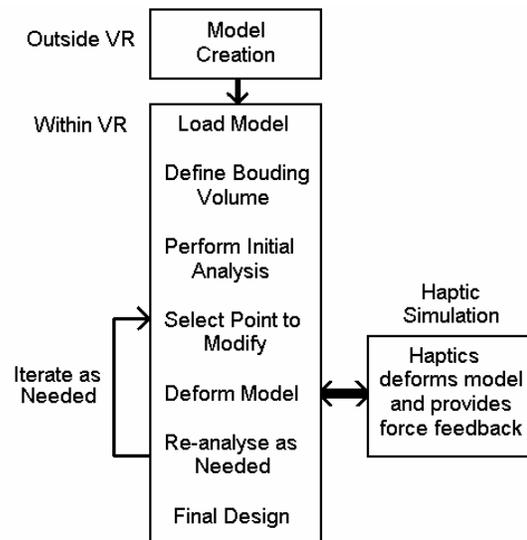


**5. Conclusions:** An intuitive environment for observing the effect of shape changes on stress distributions has been developed. Further work is continuing on this project to allow for material nonlinearities and plastic deformation.

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