Ph.D. PROPOSAL

THE DEVELOPMENT OF A COLLABORATIVE VIRTUAL ENVIRONMENT FOR FINITE ELEMENT SIMULATION

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26 October 2000

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Abstract

Design process has become more complex and multidisciplinary in nature. Often we find different disciplines are geographically distributed making the engineering design communication more difficult. Solving the communication problem would contribute to a more efficient decision making process in engineering design. Virtual reality has become an increasingly familiar part of the science of visualization and communication of information. This, combined with the increase in connectivity of remote sites via high-speed networks, allows for the development of a collaborative distributed virtual environment. With the availability of high speed computing, simulation with virtual reality can be used as a platform for designers in different geographic locations to communicate with each other assimilating the real meeting environment to enhance decision-making process in engineering design. This paper proposes a research project to develop a distributed collaborative virtual environment that allows designers from multidisciplinary backgrounds in geographically dispersed locations to collaborate during design development process. A special interest is given to finite element simulation since it is the most common engineering analysis method used by designers. The environment described allows designers to communicate and interact in a totally immersive environment. Multiple users can log on at the same time and each will be represented by an avatar. The designers have the ability to view and manipulate a 3D virtual reality model while communicating interactively to each other. This environment supports several graphical file and audio formats. The real time or near real time interaction is the most critical issues to be addressed in order to make this type of environment feasible. Several methods will be explored including domain decomposition techniques, hierarchical feature extraction, parallel executions in distributed environments.
INTRODUCTION

Communication between engineering designers at different remote locations has been limited to telephone, email, fax, and video conferencing. With the advent of information technology and virtual reality, this communication hurdle and interaction barriers can be overcome. The use of virtual immersive environment has made the distant communication similar to the actual meeting environment where designers can see each other and interact just like in the actual environment. However, there remain several issues to be resolved including real-time interaction and database management. Recent development has been limited to the state of the art of virtual reality technology such as CAVE environment.

One of the major challenges in developing such environment is to get the real-time or near real-time response after a particular design has been altered. For example, the finite element analyses for a large aircraft wing that may consist of thousands of elements. Once changes have been made on a particular section of the wing, the recomputation of the FEM is needed and this process is computationally expensive. Hence, the real-time or near real-time results cannot be achieved. Another issue has been the complexity of the problems worked with. For examples, a huge finite element data with thousands of nodes and element to work with will certainly requires a tremendous amount of computation time. Therefore new computations techniques need to be develop to facilitate fast computation time. This will include implementation of parallel and distributed computing, and hierarchical feature extraction. Since the primary aim of the computer visualization method is not to immediately produce a highly precise output, rather it is more towards guiding designers in decision making process, some level of accuracy can be compromise in lieu of fast computation time. The other is the speed of the connection lines, which contributes to the lag time when information is sent to other designers. Eliminating this lag time is important, but another fundamental issue still exists. Users should be able to understand a design representation in a meaningful way especially when dealing with a complex design data or model.

Virtual Reality provides users with a new dimension in supplying them with a life-like setup to enable them to interact and manipulate object just like in a real situation. Many virtual reality technologies have been developed that provide means of interfacing and exchanging data with other programs for seamless transition from visualization to solution or vice-versa. This would enable the virtual reality technology to be incorporated into engineering design area. This is an added advantage that could enhance the engineering design and optimization process in which designers could see the effect of changing the design parameters not only in a 2-dimensional graphical form but also in a 3-dimensional virtual reality model.

The purpose of this research is to develop a collaborative virtual environment (virtual room) where designers at different geographic locations could combine their expertise in solving shared problems by allowing them to simultaneously view, interact and discuss sophisticated computation models. The specific issue that will be addressed is the simulation of finite element analysis in virtual environment that is the most common engineering methods used by designers. In this environment, designers at distributed locations would be able to view and manipulate a three dimensional design, make changes to the design and see the effects of design changes in real-time on near real-time. There are several techniques that will be looked in order to implement such environment including parallel processing and distributed computing, domain decomposition technique and hierarchical feature extraction.

LITERATURE REVIEW

Collaborative Virtual Environment (CVE)
Various Collaborative Virtual Environments (CVE) have been developed in the area of distant learning, games and engineering. This section will describe two distinct collaborative virtual environments; window-based collaborative environment and totally immersive collaborative environment. Window-
based collaborative environment refers to a x-windows type where users at different location are represented by a video screen with voice capability. Another window may be used to represent a design model or subject of discussion. It has some similarity with video-conferencing done in an x-windows environment. In a totally immersive collaborative environment, users at different geographic locations are immersed in a single shared environment with each represented by an avatar.

A system called IRI (Interactive Remote Instruction)\(^2\) at Old Dominion University developed a geographically dispersed virtual classroom by integrating high-speed computer networks and interactive multi-media workstations. Each student participates using a personal workstation which can be used to view multi-media notebook, and to interact via video/audio and shared computer tools. Each workstation is equipped with a speaker, microphone and video camera.

A collaborative and completely immersive tennis game\(^3\) has been developed by a group of researchers at MIRALab, University of Geneva. In this environment the interactive players that were separated 60 km from each other were merged into the virtual environment by head mounted displays, magnetic flock of bird sensors and data gloves. The Virtual Life NETwork (VLNET)\(^4\) which is a general purpose client/server network system is used for managing and controlling the shared networked virtual environment via ATM network using realistic virtual humans (avatars) for user representation. These avatars support body deformation during motion. They also represent autonomous virtual actors such as the synthetic referee, that made part of the tennis game simulation. A special tennis ball driver animated the virtual ball by detecting and treating collisions between the tennis ball, the virtual rackets, the court and the net of the court.

The teleimmersion group at the Electronic Visualization Lab (EVL) at University of Illinois at Chicago has been involved in the development of virtual environment enabling multiple globally situated participants to collaborate over high-speed and high-bandwidth networks connected to heterogeneous supercomputing resources and large data stores. Among the projects developed are CAVE Research Network (CAVERN)\(^5\), Collaborative Image Based Rendering (CIBR), Laboratory for Analyzing and Reconstructing Artifacts (LARA), Tele-Immersive Data Explorer (TIDE), Tandem \(^6\), Collaborative Architectural Layout Via Immersive Navigation (CALVIN) \(^7\), Narrative Immersive Constructionist/Collaborative Educational Environments (NICE) \(^8\), The Round Earth Project \(^9\) and Computer Augmentation for Smart Architectonics (CASA).

Collaborative Virtual Environments (COVEN) \(^10\) is a European project that seeks to develop a comprehensive approach to the issues in the development of collaborative virtual environments (CVEs) technology. COVEN brings together twelve academic and industrial partners with a wide range of expertise in Computer-Supported Co-operative Work, networked VR, computer graphics, human factors, Human-Computer Interaction, and telecommunications infrastructures. The essence of Collaborative Virtual Environments (CVEs) is the use of natural spatial metaphors, together with the integration of participants and data within a common spatial frame of reference. Combined with high representational capacities, this creates the potential to support a broad range of co-operative applications in the diversified fields of design, visualization, simulation, training and education, as well as entertainment. The overall objective of the COVEN project is to comprehensively explore the issues in the design, implementation and usage of multi-participant shared virtual environments, at scientific, methodological and technical levels. This is performed through a set of concurrent and related threads of work focused on different issues at application, system, network and human factor levels. The project is based around the Distributed Interactive Virtual Environment (DIVE) and Model, Architecture and System for Spatial Interaction in Virtual Environments (MASSIVE). DIVE is an internet-based multi-user VR system where participants navigate in 3D space and see, meet and interact with other users and applications. The DIVE software is a research prototype covered by licenses. Binaries for non-commercial use, however, are freely available for a number of platforms. The first DIVE version appeared in 1991. DIVE supports the development of virtual environments, user interfaces and applications based on shared 3D synthetic environments. DIVE is especially tuned to multi-user applications, where several networked participants interact over a network. DIVE applications and activities include virtual battlefields, spatial models of
interaction, virtual agents, real-world robot control and multi-modal interaction. MASSIVE which has been developed as part of our on-going research into collaborative virtual environments. This system allows multiple users to communicate using arbitrary combinations of audio, graphics, and text media over local and wide area networks. Communication is controlled by a so-called spatial model of interaction so that one user's perception of another user is sensitive to their relative positions and orientations.

**Finite Element Analysis in Virtual Environment**

Among the early attempt to develop an interactive virtual environment for finite element analysis was done at Argonne National Laboratory. The environment developed using Cave Automatic Virtual Environment (CAVE). The finite element program employed linear finite elements with a pseudo-rigid body formulation to decouple the large rigid body displacements and rotations from the small deformations of the elastic bodies. A set of multibody dynamic equations is solved to determine the motion of the pseudo-rigid bodies. The dynamic equations for the momentum and energy are then solved to determine the elastic displacements and temperatures in the moving using unconditionally stable implicit time integration. The finite element computations and repetitive parallel assembly and solution of large global equations are achieved using parallel computing.

Haase and PreB worked on virtual prototyping systems using finite element analysis. Several crucial points such as overall system architecture, speed and intuitivity of interaction, and visualization quality of results are identified and possible solutions are suggested. This includes a flexible virtual hand interaction with adjustable finger size. In particular a level of detail technique for finite element data based on element shape functions is presented which can greatly improve visualization quality and speed as compared to common visualization approaches. This level of detail technique provides a flexible tool to adjust the exactness of visualization to rendering time (i.e., degree of interactivity) constrains. The concepts are currently being implemented within a testbed called Virtual Environment Investigation of Finite Element data (VEIFEL).

Liverani, Kuester and Hamann developed a semi-immersive Virtual Reality (VR) interface for Finite Element Analysis (FEA). The aim of this project was to integrate state-of-the-art visualization technology, VR devices, and FEA solvers into the integrated development environment (VRFEA). VRFEA was designed to overcome the integration gaps between VR and FEA. In the environment the designer uses immersive VR tools to manage a FEA model, manipulate nodes or shells, create or adjust the mesh, specify boundary conditions and visualize the results.

Yeh and Vance at Iowa State University have used VR approaches in Finite Element Analysis (FEA) to evaluate "parameter sensitivity" and facilitate design. This research project incorporated free-form deformation techniques and sensitivity analysis into the virtual world such that the designer can easily implement analysis-based shape design of a structural system where stress considerations are important. NURBS-based free-form deformation (NFFD) methods and direct manipulation techniques are used as the interface between the VR interaction and the finite element model. Sensitivity analysis is used to allow the designer to change the design model and immediately view the effects without performing a re-analysis.

Yagawa, Kawai and Yoshimura developed a "mesh-invisible" finite element analysis system in a virtual environment controlled with a three-dimensional mouse and a stereo display. The main purpose of this project was to develop new pre- and post-processing techniques that can easily deal with large-scale 3-D finite element analyses named “WH” is newly developed in a virtual reality environment. This system has two main features in user interface design to efficiently control large-scale 3-D analyses in the virtual reality environment. The first feature is an automatic adaptive analysis based on posteriori error estimation and a global h-version remeshing technique. The second feature is a new visualization capability for analysis conditions and results whose processing speed is independent of the scale of analysis. Owing to these features, a mesh is virtually hidden from user and then a “mesh-invisible” finite element analysis system can be realized.
RESEARCH ISSUES

The environment proposed allows people in different geographic location to meet and discuss design problems in a virtual immersive environment (virtual room). The virtual room serves as a meeting environment where designers can meet, communicate, analyze design problems in the form of 3D virtual object, make changes to design parameters and display the effect.

Let us take a good example problem of a large structure - a wing for a large transport aircraft. This kind of structure normally consists of a lot of substructures such as metal plates, spars and ribs in different geometric forms and with different types of material properties. The common type of engineering analysis done on this structure is aerodynamic testing and stress analysis due to different type of loading and operating conditions. In order words, a finite element analysis is one of the major methods of analysis. For a large and complex structure that consists of a huge number of elements, the analysis process is time consuming and computationally expensive. Generally in engineering applications, the design process is very iterative. Any changes to design parameters would require rerunning the engineering analysis. This would add another considerable time constraint to the design cycle. Design changes generally can be classified into two categories: local and major or global changes. For example, the change of material type or properties on a panel within a wing structure that does not alter any geometry can be viewed as a localized change. On the other hand, changing the length of wing chord and span can be viewed as a major or global change. The effect of local changes may not affect greatly the overall design domain, whereas major design changes may change the entire scope of the design.

Therefore, this research will address the following research issues:

**Issue 1:** How can virtual reality be used to assist geographically dispersed designers in making decisions pertaining to a complex engineering problem (finite element analysis) that will also contribute to an efficient decision making process?

**Answer:** In this research, the virtual reality technology will be employed to develop a virtual collaborative environment where designers situated at different geographic locations can communicate in a single shared virtual environment. Complex engineering problems (large finite element data) are difficult to be discussed over telephones or even video conferencing. The sense of ‘reality’ in a 3-dimensional environment can not be simulated in such systems.

**Issue 2:** Given a huge amount of engineering data (finite element in this case) how can they be visualized graphically and be made available in a fast and real time to geographically distributed designers?

**Answer:** The major issue as highlighted in the previous section is to achieve real-time or close to real-time response. This means that as changes are made to the design, the results of the analysis should be retrievable in real-time or close to real time. If this issue cannot be resolved, the purpose of creating such collaborative environment is defeated. The research areas in the following sections are pertinent and worth to be investigated in order to address this particular issue.

**Parallel Processing and Distributed Computing**

Imagine a FE analysis is being done on a reasonably large aircraft structure. Everybody in the virtual room could visualize and manipulate the structure using virtual tool such as virtual glove or 3D mouse. Let say, some designers suggest some changes to be made on certain parameters of the design. The only way to see the effect of those changes is by rerunning the analysis. For a large structure, this is a computationally expensive process and time consuming. The execution of a large-scale problem can be made faster by employing parallel execution together with domain decomposition method (DDM) which will be described in the following section. The simulation system is divided into regions, and the responsibility for executing each region is assigned to a specific processor. For distributed computing, a
data management scheme has to be employed. This is to allow load distribution management in order to facilitate real-time interaction. Each design subdomain might not have a uniform computing load. Therefore, a global assessment agent is required to evaluate the level of computing load of each subdomain and distribute them uniformly to the relevant processors. A data updating system is another issue to be addressed. Users in different geographic locations should be supplied with the most recent information in real-time. If any changes are made to any design data, the information should be updated and displayed to each user.

There is another hidden advantage of using collaborative virtual environment (CVE) in engineering application. Using high-powered machines to solve the problem seems to be a good alternative. However, these machines are not accessible to every designer due to their expensive cost. CVE offers great help for designers deprived of this access to communicate in real time to discuss an engineering analysis with a designer who is in charge or the CVE.

**Domain Decomposition Method and Multigrid/Multilevel methods**

In order to facilitate fast computation, the large-scale design domain may have to be divided into subdomains using the concept of domain decomposition method (DDM). Each domain will be evaluated depending on the computational load required to execute the analysis.

The fundamental idea behind all multigrid methods is to compute using different scales in order to obliterate error components of different scales. Multigrid methods are well known to be difficult to work on nontrivial problems. Yet they have flourished during the 1980’s and 1990’s to become quite standard iterative methods. This is due to their rapid convergence rates and low work estimates. Domain decomposition methods are flexible iterative methods for the solution of linear and nonlinear systems of equations that arise from discretizations of very general classes of partial differential equations. Motivations for the use of these methods include the potential for parallelization, the ability to deal with equations on complicated geometry, the ability to deal with equations that exhibit different behavior in different parts of the domain, and the superior convergence properties even on sequential machines. This concept is very relevant especially when dealing with a large-scale problem. A large design domain can be divided into smaller domains where they will be processed in parallel using parallel machines. This method would enable results for a massive design to be processed in real-time or near real-time.

Finally the concept of parallel processing and distributed computing will be employed to solve the perturbed problems. Interestingly, the three concepts mentioned above are interconnected to each other. A large-scale design will be evaluated in term of computational load once changes are made. The pollution error analysis will be done to evaluate the effect of the design perturbation on the overall design. The concept of domain decomposition will be coupled with parallel perturbation. The design will be split into several pieces and solved separately on parallel machines.

**Pollution Error in finite element analysis**

Research work in this area has been developed by Texas Institute for Computational and Applied Mathematics (TICAM). In a given small patch of elements, the error in the patch are divided into two components: The *local (or near-field) error* which is the response in the patch when the domain is loaded only by the residuals of the finite element solution in the patch and a few surrounding mesh-layers (the near-field residuals), and the *pollution (or far-field) error* which is the response in the patch when the domain is loaded by the residuals of the finite element solution in the elements outside the neighborhood of the patch (the far-field residuals). The local error can be estimated by employing element error indicators, which are determined, by employing local computations in the patch, while the estimation of the pollution error requires a global extraction.
The concept of pollution area will be further investigated in this research to find its relevance to address issues pertaining to localized and global changes mentioned in the previous section. A method of analysis will be developed to study and evaluate the effect design changes on the overall design domain in order to avoid unnecessary recomputation of finite element analysis. For example, if changes are made on a section of a wing structure, a programming code will be written to access the effect of these changes to the overall design and decide whether to rerun the overall analysis or to run analysis on the perturbed region only. If changes are made on design parameters, an assessment tool has to be developed to evaluate the effect of those changes on the overall design. The assessment is necessary to decide whether to recompute the whole analysis or to compute the analysis of a particular region.

Hierarchical Feature Extraction
The virtual meeting environment does not serve as an analysis venue for detailed engineering analysis. The main goal is to assist designers in the process of decision-making. A large design problem normally contains a massive graphical data in the form of nodes, elements and polygons. Displaying all these details in graphical form may require a long execution time. A highly accurate analysis result may not be desirable since it is computationally expensive. In this research, this issue would be addressed. After all, the purpose of the graphic visualization part is to steer the engineering analysis and guide designers in making decision. Once the final decision has been made, the actual detailed analysis can be made by making tradeoff between accuracy of the finite element analysis and the quality of the graphical representation. The use of domain decomposition method together with multigrid and multilevel method can be used to achieve this goal. In multigrid and multilevel methods, the coarseness of the finite element grids can be varied and different grid scales size can be used to reduce the computation cost and time. This would require error assessment as to what grid scales should be used for a particular subregion.

RESEARCH FRAMEWORK

Many virtual reality technologies have been developed that provide means of interfacing and exchanging data with other programs for seamless transition from visualization to solution and vice-versa. There are several CAD packages and modeling language that can be directly used with a lot of virtual reality packages including AutoCAD, OpenGL and Virtual Reality Programming Language (VRML) and Pro/Engineer. The development of high-speed networking and Internet connections is two major achievements in the long distance data communication. The integration of the virtual reality technology and high-speed data communication has made the concept of collaborative virtual environment an important breakthrough in engineering design.

Although significant developments have been made in the area of collaborative virtual environment, the recent developments in the area of collaborative virtual environment have mainly been limited to the use of the state of the art technology such as CAVE that is expensive to users.

The objective of this research is to develop a multi-platform collaborative virtual environment (CVE) where designers from multidisciplinary backgrounds can communicate with each other in a meaningful and useful way via the internet or high speed connection lines such as ATM (Asynchronous Transfer Mode). This environment consists of a virtual room (VRoom) where designers at different geographic locations could get together in a windowless virtual environment. Each designer can see other participants in avatar form, communicate, and manipulate the design model loaded to the room. The ultimate goal of the CVE research is not merely to reproduce a real face-to-face meeting in every detail, but to provide the “next generation” interface for collaborators, at remote locations, to work together in a virtual environment that is seamlessly enhanced by computation and large databases. When designers are tele-immersed, they are able to see and interact with each other and objects in a virtual environment. Their presence will be depicted by life-like representations of themselves (avatars) that are generated by real-time modeling techniques. The framework of this research project is described in the following sections.
**The immersive environment - VRoom**

The first part of this research work will involve the development of a virtual meeting room where designers in various locations meet in a single virtual environment. The virtual meeting environment does not serve as an analysis venue for detailed engineering analysis. The main goal is to assist designers in the process of decision-making. VRoom main focus is in supporting collaborative visualization of engineering data, which can be in the form of design model, finite element analysis model or graphical representation of design data such as graph morphing technique GMORPH\textsuperscript{23}.

The virtual room serves as a venue for designers from different geographic location to meet in a shared immersive environment. The VRoom developed in this project serves as a meeting environment where designers can meet, communicate, analyze design problems in the form of 3D virtual objects, make changes to design parameters and display the effects in a totally immersive environment. Each designer will be able to see each other, communicate and interact. The facilities in the virtual room would include virtual board, control panel and model room. The finite element model can be loaded to the model room using the control panel. Each designer will be able to point and manipulate the design model loaded to the model room using virtual hand or pointers designated in different color for different designers. The designers using the environment would require virtual reality hardware; pinch glove, head mounted display and positional tracker. The software used to create the virtual room is WorldToolKit (WTK)\textsuperscript{24} which consists of a set of C functions that provide drivers for managing the peripherals used for interacting with the virtual world.

The virtual room consists of a room bounded by four invisible walls, a ceiling and a floor. The geometry are created using a neutral file format (NFF) which define the coordinate points (vertices) of the object and the polygon connectivity. Objects created using WTK are ordered hierarchically into a nicely structured tree called scenegraph. The structure defines objects into parent-child relationship which is significantly useful for building a virtual environment. The walk-through simulation is done with the help of a 3D mouse or a regular mouse.

There are two distinct virtual rooms developed in this project. The first is with a set of pull-down menus and the other is borderless without any menus and window-type frame. The VRoom is made borderless

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**Figure 1** – Virtual Collaborative Environment for finite element simulation
with the aim of making the environment as close as possible to a real-life meeting room when viewed using immersive hardware like Head-Mounted Display (HMD) and Stereoscopic glasses. The one with pull-down menu is designed to be used by the VRoom manager who is in charge for managing the virtual meeting. There is a communication protocol set up to manage the virtual meeting. The manager is responsible for managing the meeting, and granting permission to save, load, manipulate or make changes to the design model. He or she is the only one who has the access to the database, has the right to grant or deny entry to virtual room and has the right to exploit or change the configuration or setup of models loaded to the virtual room. This is to ensure a virtual meeting run in an orderly manner. The features of the VR menu include the functions to load and save the design model, exit the virtual room, change the scale and position of the model, rotate the model around and load another model. All the controls described are performed using mouse clicks. The borderless and menuless virtual room was designed for the remaining participants of the virtual room. Each of them will be able to speak to the rest of the participants of the room, visualize the data or models loaded to the room and walk around the room.

The VRoom supports several file formats from common CAD packages and modeling languages including AutoCAD, VRML, 3D Studio and Pro/Engineer. Each user will be represented with an avatar as shown in the figures. Whenever a participant moves around or points at a certain

**Collaborative Environment**

The purpose of this part of the research is to make a more realistic engineering simulation and visualization environment for geographically dispersed designers. The proposed overall collaborative virtual environment concept is illustrated in Figure 2.

![Collaborative environment](image)

**Figure 2** – Collaborative environment

The collaborative part of the research involves collaborative interaction and manipulation, data management and connectivity to various locations. The issues to be tackled are:

- **Communication in teleimmersive environment**
  This typically involves the use of audio conferencing and user representation in a shared virtual environment. It also includes the use of avatars to provide a representation of the participant in the
environment and to convey gestural cues (such as pointing at objects, nodding and shaking of the head) that augment audio communication.

- **Synchronous collaboration**
  Persistent environments assume one’s ability to work in an environment at the same time with other participants synchronously. Any changes made to the environment must persist for when the other participants return.

- **Collaborative interaction and manipulation**
  Tools to enable participants to interact and manipulate shared objects and datasets being visualized in the environment are needed. These tools must guarantee that proper consistency is maintained across each participant’s view of the environment, especially when multiple participants attempt to modify the same shared object.

- **Connectivity with external resources**
  The data that end users want to access in a complex teleimmersive environment will likely reside on external database or be generated by simulation codes on workstations network. The data may consist of 3D models, collected field data, computed data, virtual environment data, and video and audio streams. Although some simulations may not be initiated in the virtual environment but on a desktop workstation, the simulations will still need to direct the result of computations to a data store that the virtual environment can access. Hence, end users will need tools to enable them to easily interface their existing non-VR tools or applications with the virtual environment.

The VRoom collaborative network was developed using the WorldToolKit (WTK) networking capability which enables us to build applications that can asynchronously communicate over an Ethernet between several UNIX workstations. This allows distributed simulations to be created where a mixture of SUN and SGI workstations support a single simulation. In this project, up to 16 users can log into a single virtual world where each user can see other people in the world. A Graphical object or avatar representing each user in the simulation is located at the user’s viewpoint. WTK network applications share a common API so that a single application can be run on both PC and UNIX platforms without modification. WTK’s networking capability is built upon IP (Internet Protocol) and UDP (User Datagram Protocol) guidelines. This means that one can use this capability on top of pre-existing networks without causing problems to the entire network. This also means that it is possible to multicast messages onto the Internet for geographically disbursed simulations.

Each user in the VRoom environment will be represented by an avatar which location indicates the viewpoint location of each user in the VRoom 3-D space. The viewpoint location and orientation of every user are continuously sent and updated at every frame rate to ensure a synchronous collaboration.

The database for maintaining the VRoom including the files and images needed for virtual meeting purposes resides on the server machine which is only accessible to the VRoom manager. For network security purposes, only a registered member can get access to the virtual meeting environment. Once connected to VRoom server, a user can work simultaneously or asynchronously with other users. The environment will persist even when all participants have left it. The client consists of the VR display device (regular monitor, HMD or ImmersaDesk™, etc.) and the software necessary to allow the setting up of the VRoom. The client also provides the basic capabilities for streaming audio and for rendering avatars to allow participants to communicate effectively with one another while they are immersed in the virtual environment. A more detailed

The audio capability for VRoom environment was developed using a program called Speak Freely which is currently available at no cost. This is a program that allows two or more people to conduct a real-time voice conference over the Internet or any other TCP/IP network. It supports a variety of compression protocols, such as GSM, ADPCM, LPC, and LPC-10. The cryptography-enabled version includes IDEA, DES, and limited PGP encryption capabilities for protecting the privacy of important
voice conversations. The program is available for multiplatform including UNIX, Windows 95/98/NT, and Linux.

**Finite Element Simulation in immersive environment**

Imagine a scenario where we have a large finite element model consisting of different substructures with intricate geometry and different materials. Designers may decide to make localized changes to a sub-design. For example, in an aircraft wing design, we commonly find a number of panels that are made from different materials and physical parameters. In this particular situation, if we decide to replace a panel with different properties and dimension we need to isolate the sub-design from the rest of the design and at the same time we need to study the impact of changing a sub-design to the overall design. In finite element context, when this situation arises, we cannot afford to rerun the whole analysis of the design. We may need to find a way to isolate the sub-design and run the analysis on that particular sub-design. This technique if achievable would save a lot of computational time and make the intent of this research, which is to develop a collaborative virtual environment, a reality.

The system architecture of the finite element simulation in Virtual Environment is shown in Figure 4.

![Figure 4 – System Architecture of Vroom running Virtual FE Simulation](image)

The graphical module handles the importing of design model into VRoom. It stores the loaded file in VRML format which can be directly loaded to each user environment from the URL address. It also provides the necessary process needed to feed a design model to the next process, the FE module.

The FE module handles all the pre and post processing operation and integrates an FEM solver, the Adaptive Finite Element Application Programmers Interface (AFEAPI)²⁶. The preprocessing part is done using HyperMesh™ which can easily be interface with the graphical module. In this manner user can identify and specify the location and type or constraints and forces applied to the design model. AFEAPI provides a simple infrastructure for users to develop their own parallel adaptive hp finite element codes. AFEAPI will be responsible for the dynamic data structure, mesh partitioning and redistribution and optionally linear equation solvers. AFEAPI employs faster computational techniques using parallel processing. The results from AFEAPI are then read into a visualization package called Vis5D²⁷, which
will display the post processing graphics in the VRoom environment. The advantage of using Vis5D is that it can save the visualization graphics such as the FE models deformation and stress distribution in the VRML format which can conveniently be viewed in the virtual environment. The detailed setup of the FE and Graphical modules is shown in Figure 5.

![Figure 5 The FE and Graphical Module](image)

**PROGRESS & FUTURE WORK**

The following work has been completed:

- The development of VRoom
- The Collaborative infrastructure
  - Avatar design
  - Audio capability using SpeakFreely
  - Model uploading to VRoom from URL site
- Graphical Module
  - Converting model to VRML
  - Reading VRML file from URL location
  - Model manipulation – stretching geometry, placing and specifying force and constraints
- FE Module
  - Translating graphical representation to HyperMesh™ input file
Future work:

- The Collaborative infrastructure
  - Improvement of avatar design
    - Object picking
    - Avatar labeling or identification

- Graphical Module
  - Improvement of Model manipulation
    - Mark an area for FE assessment/computation
    - Improvement on geometry stretching algorithm
  - VRML 2.0 capability using WTK 9.4

- FE Module
  - Direct and automatic linking between Graphical Module, FE Module, FE Solver and Vis5D
  - Hierarchical Feature Extraction to facilitate fast or real time FE computation
    - Multigrids
    - Sensitivity analysis & Optimization
    - Accuracy and Error trade-off

- Test Problems
  - 2D and 3D FE analysis

The research is expected to be completed by Jan 2001.
REFERENCE


