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Extended Abstract

1 Introduction

Reasoning about complex physical phenomena is an activity that occurs in fields as diverse as scientific exploration, weather forecasting, and military mission planning. Teams of experts often use computer visualization, simulations and automatic problem solving to gain insight into a problem, to evaluate possible strategies, to build an initial set of solutions, or to validate hypothesis. We believe that an *integrated* framework, with support for all the activities outlined above, would be extremely useful for such applications. The system we envision, and of which we have built a prototype, has the following characteristics:

1. It provides a realistic graphical simulation of the environment
2. It allows the user(s) to intuitively and effectively interact with entities in the environment
3. It integrates scientific visualization techniques, with an emphasis on interaction and multi-resolution display
4. It allows shared, collaborative multi-user interaction
5. It supports distributed computation on network clusters
6. It offers a rich suite of multimedia tools for support of teamwork from multiple remote locations connected to a network

The novel contributions of our approach are mainly in the following areas: (i) The ubiquitous use of 2D and 3D multi-resolution triangulations for geometric searching, multi level-of-detail representation, and hierarchical spline support for multivariate functions; (ii) The multi-modal user collaboration support, for shared access to the geometric database, and effective group work across a network of workstations; (iii) The fusion of virtual environments, visualization and multimedia tools and techniques into an integrated framework to aid and partially automate the problem solving process.

In this paper, we describe the main components of our system, and outline algorithms and data structures used to achieve the efficiency and real-time response needed in an interactive environment. We then describe the architecture of our collaboration and distribution functionality layer, and the integration of multimedia, network-based communication tools. Finally, we report on the application we are currently targeting: The simulation of air/land/sea defense scenarios, and the modeling of radio frequency energy propagation in the presence of terrain and atmospheric obstacles for airborne data collection management.

2 Virtual Environment Framework

Extensive research and prototype development and evaluation is being currently done in the field of Distributed Virtual Environments (DVEs) (see for example [25, 24]).

Several powerful extensive DVE systems have been developed for large scale collaboration over the Internet. Systems such as DIVE [12], MASSIVE [19],

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and NPSNET [21] provide excellent starting points for investigating and developing even more powerful and sophisticated systems. Our own system evolved from earlier in-house prototypes [1, 4].

The aim of our project is providing an effective tool for aiding a group of people in reasoning about a complex scenario. Typically, several users access the system from graphics workstations connected to a network. A user joins a collaborative session through a *session manager*, which establishes modalities of interaction based on the protocol chosen and the user's privileges.

A user interacts with the simulated world in several ways. He can see a representation of the environment and a visualization of the properties under study, at different levels of resolution. He can modify some of the parameters of the simulation to explore *what-if* scenarios. He can design, visualize and evaluate a strategy for the solution of the problem at hand, manually or with the help of automatic solvers. In all these activities, he collaborates with other users through the shared world as well as using the integrated video-conferencing, textual chat and messaging systems.

The four main components of our system are:

Geometry support: Hierarchical data structures and algorithms for space partitioning, position/collision queries, multi-resolution representation of geometry and functions.

Visualization support: Fast algorithms for display of geometry and functions (isosurfaces, volume rendering, streamlines, etc.).

Multimedia communication support: Plug-and-play components for audio-video teleconferencing, text-based messaging, shared whiteboard etc.

Distribution and collaboration support: Protocols for multi-user session control, management of shared worlds, constraints for collaboration, etc.

In the following we will detail each of these four components.

2.1 Geometry Support

A critical subsystem in all synthetic environment systems is the *geometric engine*, or the software module responsible for creating a realistic view of the simulated world, and for allowing users to interact with it. In a typical scenario, a system requires the display of several objects, that move and must behave realistically.

Additionally, the class of applications we are targeting demands the capability of representing scalar and vector fields defined in three-dimensional regions of space, in planar domains or over the surface of an object. The representation should allow fast qualitative estimation of function qualities as well as accurate measurements of function values and properties.

The geometric substrate of a our synthetic environment system provides efficient data structures and algorithms for:

1. Shape representation
2. Dynamic object insertion and deletion
3. Object animation (motion, non-rigid transformation)
4. Object location and closest point queries
5. Collision detection and contact analysis
6. Visibility ordering and culling
7. View-volume clipping
8. Real-time high-quality rendering
9. Hierarchical space partitioning data structures
10. Multi-resolution representation of geometry and scalar/vector fields

Among the space partitioning data structures available to speed-up of processing and display of geometric data, the most relevant are probably *octrees* [23], *k-d-trees* [8, 9] and *BSP-trees* [18].

We propose the use of simplicial-based hierarchical data structures, coupled with efficient point location data structures, to provide a unified framework for the functionalities needed in our synthetic environment. Unstructured tetrahedral grids are extensively used in finite element analysis, and triangulations are pervasive in computational geometry. Multi-resolution triangulation hierarchies [10, 14] have been proposed for representation of terrains and volume data.

A 3D regular (weighted Delaunay) triangulation [16] can be built incrementally, via point insertion and topological flipping. A history DAG can be used in the incremental algorithm to allow the efficient location of points within the triangulation. Moreover, a Power (weighted Voronoi) diagram [2] (eventually of order k), can be easily computed (by duality) to allow fast answers to closest point queries.

Using a hierarchy of triangulations has several advantages. Simplicial complexes are acyclic with respect to visibility ordering [15]. This means that, given a viewpoint, it is possible to order the cells of the complex in a sequence such that if A obstructs B, then B precedes A in the sequence. This property can be preserved in a hierarchy. Moreover, a hierarchy of simplicial complexes naturally defines a multi-resolution representation of the geometry, useful for example in multi-level of detail modeling of terrains, and allows fast point location and other types of queries when associated with appropriate data structures.

We also use 2D and 3D triangulations as support meshes for piecewise-algebraic representation of functions. A-splines and A-patches [5] are collections of polynomials of low degree, whose zero-contour can be used to represent curves and surfaces, as well as scalar, vector and tensor fields. A-splines and A-patches are guaranteed to be smooth and single sheeted, and allow an easy formulation of derivative continuity (A-patches use degree three polynomials for C^1 continuity, degree five for C^2). Combining hierarchical triangulations with piecewise-polynomials one obtains an effective multi-resolution representation of both geometry and functions.

The power diagram of a weighted set of points can be used to partition the simulated world into a hierarchical collection of "object clusters", represented by bounding spheres.

FIGURE 1: A 2D Delaunay triangulation used as support of a piecewise polynomial (A-patches). The function is visualized as a false-colored height-map, with iso-contour curves.

2.2 Graphics and Visualization Support

We have integrated in the system a collection of algorithms and data structures to support the interactive visualization of time-varying data. Standard scientific visualization techniques are available, from isocontours and isosurfaces, to elevation maps and false coloring, to streamlines and hardware-accelerated polygonal approximation of volume visualization.

Techniques that support data reduction [6] and indexing for fast isosurface extraction [7] have also been implemented.

An examples of visualization capabilities is given in Figure 1. Figure 5 shows the equi-power surface of two directional radar antennas. Power density is represented with a translucent volume rendering, while the isosurface is a triangle-mesh extracted from the spline model. The isosurface value can be changed interactively after a preprocessing phase [7]

The use of multi-resolution models and data reduction techniques allows users to trade off speed for quality depending on their needs.

2.3 Multimedia Communication Tools

A collection of multimedia services have been developed that provide for distributed multimedia using the Shastra substrate. Services are provided for the following media types:

audio A multimedia plug-in component that provides for sampling, playback, format conversion and transmission of audio data to and from interacting hosts via the Shastra substrate.

video A plug-in component providing frame grabbing, video display, and the use of various video

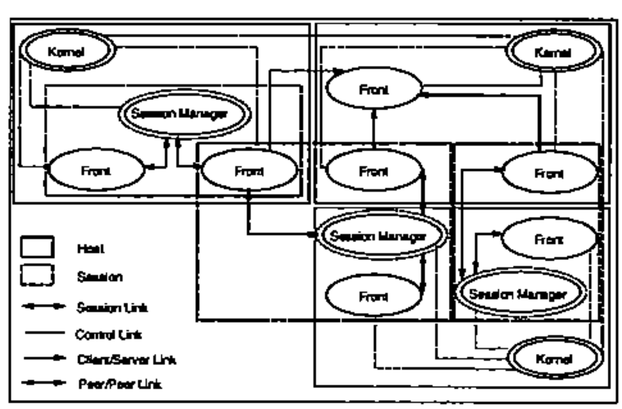


FIGURE 2: The architecture of the Shastra network collaboration substrate.

codecs (H.261, Mpeg) that transmits and receives video data through the Shastra substrate.

text chat A simple text based conferencing chat tool is incorporated within the Shastra substrate.

whiteboard A simple whiteboard object that is easily integrated into the distribution and collaboration layer providing users with a easy to use sketchpad that provides simple line figures, multiple colors, as well as spline based objects.

The audio and video components have been developed as a suite of multimedia libraries that present an identical API on multiple platforms while taking advantage of all hardware on a specific platform. Figures 3 shows the use of the multimedia components in our VE application.

2.4 Distribution and Collaboration Support

The distribution and collaboration requirements of the VE Framework are fulfilled by the use of the Shastra distributed, collaborative networking substrate [3]. Shastra is an extensible, distributed and collaborative geometric design and scientific manipulation environment. It consists of a static and a dynamic component. The static component is a CSCW infrastructure for building scientific CSCW tools. We call it the Shastra Layer. It defines an architectural paradigm that specifies guidelines on how to construct tools that are amenable to interoperation. Its connection and distribution substrate facilitates inter-tool cooperation. Its communication substrate supports data sharing and transport of multimedia information. Together they promote distributed problem solving for concurrent engineering. The collaboration substrate supports building synchronous multi-user tools by providing session management, interaction control and access regulation facilities.

In addition to the distribution, communication and collaboration framework, Shastra provides a powerful numeric, symbolic and graphics and multimedia substrate. It enables rapid prototyping and development of collaborative software tools for the creation, manipulation and visualization of multi-dimensional geometric data.

The dynamic component of Shastra is a runtime environment that exploits the benefits of the architectural philosophy and provides runtime support for conferenced tools.

The CSCW infrastructure of the Shastra system (see Figure 2) facilitates creation of collaborative multimedia tools. We adopt an abstract tool architecture that enables inter-tool communication and cooperation. It supports remote task invocation and brokering.

3 Application: Reasoning about Radio Frequency Energy propagation

Planning a path to avoid flying in radar-covered zones, managing airborne Radio Frequency (RF) data collection, or optimizing the placement of RF emitters for best coverage are all activities that require reasoning about propagation of RF energy emitted by multiple sources in a 3D environment. While automatic path planning or optimal source placement can be used to compute an initial set of solutions, the intervention of a human expert is still required to refine and validate the output of such algorithms.

A distributed, collaborative virtual environment that allows an efficient modeling, visualization and real-time interaction with a simulated RF-propagation scenario permits to a team of experts to work together at the solution of a large class of problems, offering a realistic and responsive simulation.

Airborne collection of VHF radio energy requires planning a flight path that passes through desirable areas of high energy, interference-free radio signals while avoiding threat for the airplane or no-fly zones [13]. This path-planning can be done automatically or by expert human operators. In both cases, a three-dimensional representation of the propagation characteristic of RF energy is required in order to support visualization on graphics workstations, and computation and analysis of prospected solutions. Our system takes into account the effect of obstacles (reflection and refraction), and is able to visualize RF energy, antennas, terrain model, weather conditions, designated targets, air bases and other relevant parameters.

The availability of an effective representation of RF energy propagation in a 3D environment would benefit other important applications as well. For example, commercial broadcasting networks are interested in analyzing the extent of propagation of RF energy over a given geographical area. Cellular telephony in an urban setting requires optimal placement of radio sources/receivers in the presence of multiple 3D obstacles and reflecting surfaces [17, 22].

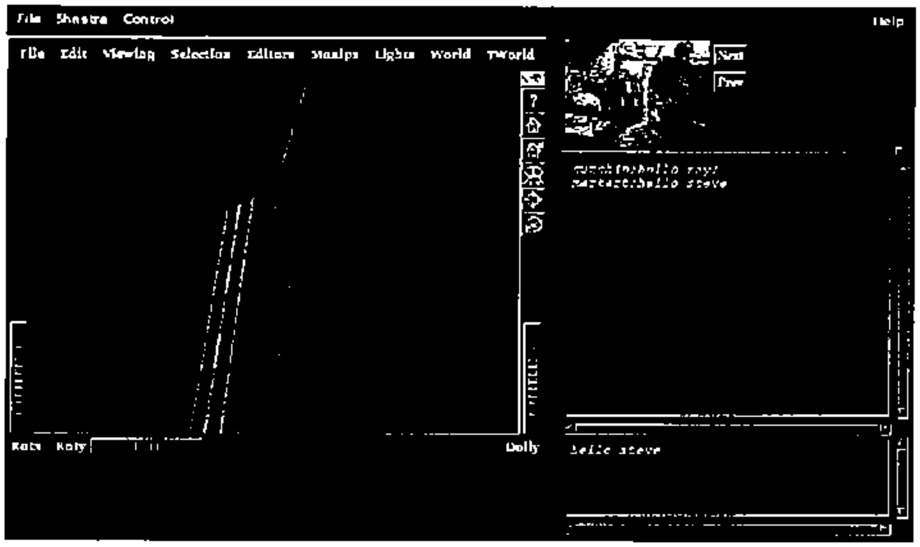
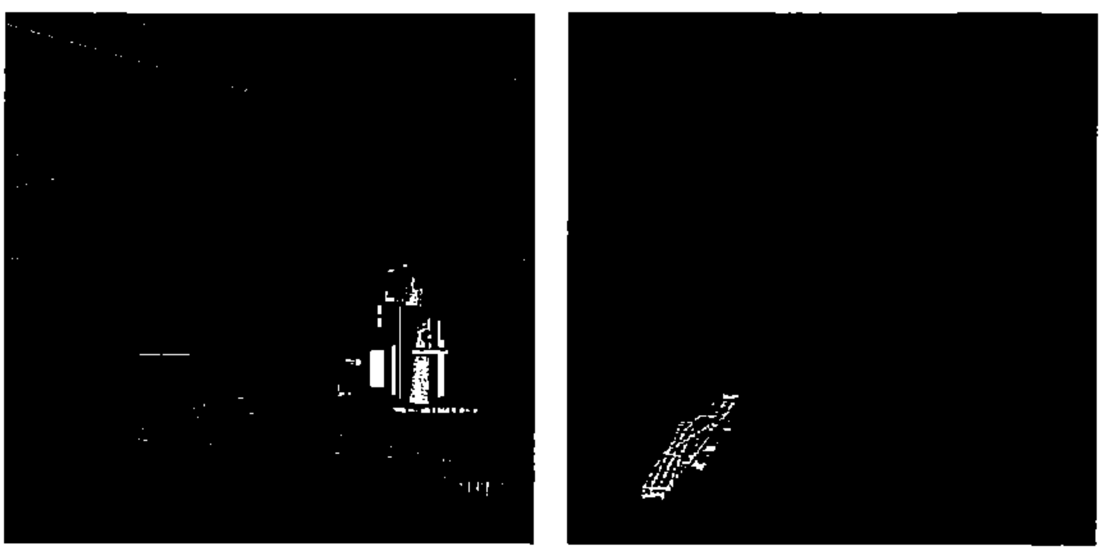
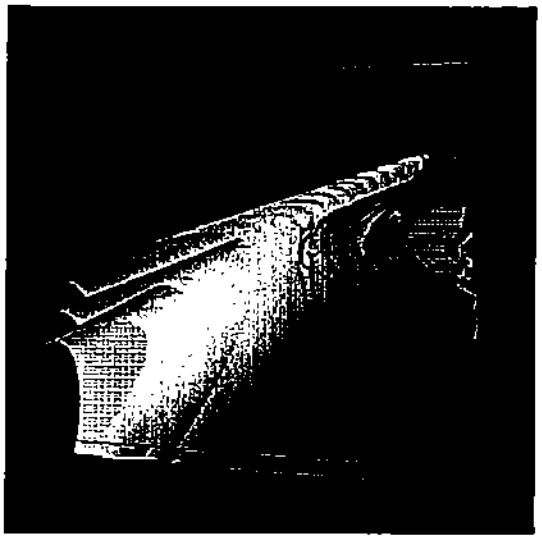


FIGURE 3: The graphical interface of our system, including video, audio and text messaging communication tools, and the VE window.

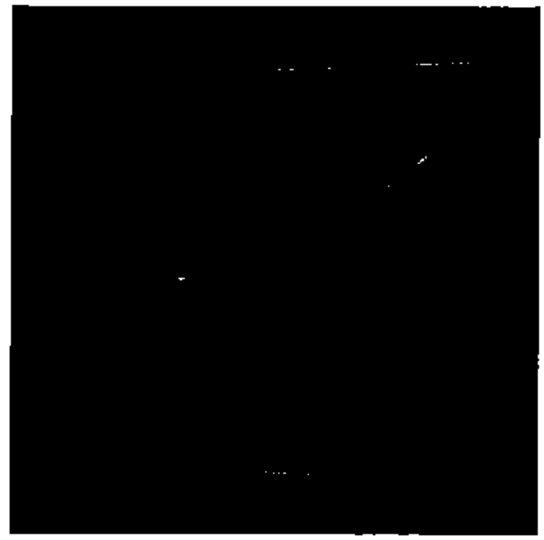


(a) (b)

FIGURE 4: Two views of the Virtual Environment. (a) The deck of an aircraft carrier with an associated triangulation used to keep track of airplane positions. The triangulation visible above the sea (white wireframe) track airplanes flying in the zone. (b) A radar simulated by a 3D triangulation with an associated search structure is being used to track airplanes that fly by the carrier.



(a)



(b)

FIGURE 5: Two sources of RF energy (directional radar antennas) and their equi-power surface. (a) Iso-power surfaces. (b) A volume visualization of the combined electromagnetic field power-density.

3.0.1 Modeling of RF Energy Propagation in a 3D Environment

Our system allows the modeling and visualization of several sources of RF energy in a 3D environment. We can model different types of antennas, from a simple, idealized isotropic radiator, to more complex directional antennas and planar arrays. The radiation pattern of a specific antenna system can be described as a power or voltage gain as a function of the azimuth and elevation angles with respect to the boresight (pointing axis) of the antenna [20]. Electromagnetic energy radiates in the environment (often the effects of the antenna's protective cover, or *radome*, must be also taken into account). Power density at any range from the antenna is proportional to the inverse of the square of the radius (atmospheric attenuation can usually be ignored, except for exceptionally long ranges). The interaction of the electromagnetic energy with the environment is complicated. All obstacles encountered will reflect some energy, depending on their geometry and reflectivity. The reflection can cause changes in the polarization of the transmitted energy.

Idealized gain characteristics for an antenna can be computed with numerical simulation software such as NEC [11]. We are developing beam-tracing techniques to simulate the interaction of RF energy with the environment. The result is stored as a multi-resolution hierarchy of volume splines, from which one can easily extract isosurfaces or display directly as a translucent volume.

The multi-resolution nature of our representation of geometry allows computation at different levels of detail, allowing for lower-quality fast-interaction visualization when the user wants to change some of the parameters involved and have a rough idea of how they'll affect the simulation, or high-quality visualizations for accurate assessment of final results.

Algorithms for optimal flight planning can also take advantage of the search structures associated with our representation. If one simplifies the model and represents each source of RF energy as weighted point (or a sphere), then the power diagram of this set of weighted points gives a graph that can be used for simplistic flight planning. Weights can represent the power of each emitter, so that the flying distance from a source will be adjusted depending on its strength. This initial solution can then be refined manually or using more sofisticated automatic strategies.

Cronin [13] suggests the use of the 3D equidistance locus between RF iso-power surfaces as flight surfaces. While the computation of such surfaces is easy for pairs of idealized omnidirectional antennas, it becomes challenging when simulating more realistic antenna systems and taking into account the effect of obstacles.

Our system allows the computation and representation of such complex situations. We can compute the power density through the beam-tracing simulation, extract iso-power surfaces, derive a signed-distance scalar field, and finally extract its zero contour. Figure 5 shows a power-density volume rendering of the electromagnetic fields generated by two directional antennas, and iso-power surfaces.

Figure 3 shows the interface to Virtual Environment system, with the integrated multimedia communication tools, while a close-up of the VE is visible in Figure 4.

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