VIRTUAL GIS: A REAL-TIME 3D GEOGRAPHIC INFORMATION SYSTEM

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ABSTRACT

Advances in computer graphics hardware and algorithms, visualization, and interactive techniques for analysis offer the components for a highly integrated, efficient real-time 3D Geographic Information System. We have developed "Virtual GIS," a system with truly immersive capability for navigating and understanding complex and dynamic terrain-based databases. The system provides the means for visualizing terrain models consisting of elevation and imagery data, along with GIS raster layers, protruding features, buildings, vehicles, and other objects. We have implemented window-based and virtual reality versions and in both cases provide a direct manipulation, visual interface for accessing the GIS data. Unique terrain data structures and algorithms allow rendering of large, high resolution datasets at interactive rates.

1. INTRODUCTION

In the past Geographic Information Systems (GIS) were 2D, map-based systems with decidedly non-interactive rates for high resolution display. More recently one might have a 3D GIS but still would type in a coordinate or make a database query and then wait (sometimes several seconds or more) for display of the results [17]. Now with pipelined 3D graphics and efficient new algorithms for terrain visualization, we have techniques we can wed with methods for organizing geographical information to make integrated GIS visualization systems. We describe such a system here, "Virtual GIS," where we have added some new techniques for fast handling of large amounts of visual detail and developed a powerful user interface.

Virtual GIS can be used almost anywhere a traditional GIS can be used. Thus it can be used for urban planning, evaluation of vegetation, soil, waterway, or road patterns, flood planning, and many other tasks. In addition, the ability to have detailed 3D views and to jump to a different location to check the view opens new possibilities. Planners for new buildings or other facilities can see full 3D views from their prospective sites or can see the view from nearby existing buildings with their planned facility in place. Urban planners can see the layout of streets, buildings, and parks on their actual topography and can thus evaluate site lines, congestion, where sunlight strikes, etc. In addition, they can use the GIS database to display distribution of commercial activities, where schools or stores are located, where water mains run, and a myriad of other information. Emergency 911 service providers could get immediate 3D views of the areas where they must respond and, with the addition of appropriate event information in the GIS database, could also see where there are obstructions along their routes due to construction or heavy traffic. Virtual GIS is a general platform on which any of these services could be built.

The addition of immersive capabilities extends the power of the 3D GIS system. Immersion is especially useful when one must navigate an extended, complicated space or needs an overview followed by a zoom in to obtain fine detail. Thus the Army has shown great interest in immersive systems that can navigate accurate terrains down to one meter resolution and is supporting work to build a common digital picture of the battlefield. This common picture will be built on highly accurate terrain visualizations with up-to-the-minute placements of military units and groups of personnel, display of current conditions for roads and bridges, visualization of weather effects or chemical clouds, display of military symbols and tactics, and much else. All this must be presented and interacted with in real time, and the large amount of data must be organized into an efficient GIS for fast retrieval and full querying. The Navy is also interested in 3D tactical visualization systems, in this case for coastal and shallow water warfare. Finally, a system with immersive capabilities will have enhanced use for training or rehearsal. The military has much interest in training systems for rehearsing battle plans or for exploring and trying out tactical options at the command level. In addition any geography-based activity could have a training component based on a visualization system such as Virtual GIS.

2. THE VIRTUAL GIS SYSTEM

Virtual GIS is implemented using the Simple Virtual Environment (SVE) toolkit [1], a device independent library which provides mechanisms and software tools for developing virtual environment applications. SVE is based on the Silicon Graphics GL graphics library [2], and Virtual GIS has been run on a number of different hardware systems with GL support, including Silicon Graphics, Hewlett Packard, and Kubota Denali workstations. Powerful graphics hardware such as a Silicon Graphics Reality Engine [3] is required to render the highly complex datasets at real-time rates. Our goal in designing the Virtual GIS system was to achieve real-time rates in all of its operations. We defined "real-time" to mean speeds of at least 15 frames per second and latencies for interactions of the order of 1/10 to 1/15 of a second.

Virtual GIS can be used either with a workstation window-based interface, or with an immersive virtual reality interface. In the immersive environment, users wear a head-mounted display (HMD) and hold a three-dimensional mouse controller, with six degree-of-freedom trackers attached to both the HMD and 3D mouse. The head-tracking allows the HMD graphics to be generated in accordance with the user’s viewpoint, so that the user feels a sense of presence within the virtual environment. The tracking of the 3D mouse is used in conjunction with a cursor on the HMD screens to provide the functionality of a 2D mouse within the immersive environment, for tasks such as selecting objects and menu items. Users can depress a button on the 3D mouse to “fly” in the direction they are facing.

The conventional window-based interface parallels the functionality of the immersive interface. The 2D workstation mouse can be used to rotate the user’s viewpoint, move through the environment, select objects, and pull down menus. The user’s view is displayed in a workstation window.

Use of Menus

The familiarity of menus from the 2D paradigm and the ability of well-designed menus to organize commands into easy-to-use sets makes them attractive in 3D virtual environments as well. Still, important choices have to be made when using menus in an immersive virtual environment application: should they pop-up or remain visible; should they be stationary in world-, head-, or maybe hand-coordinates; and how is a menu item actually selected? After work by us and others [18] that has shown the drawbacks of having menus as 3D objects in the virtual environment, we have opted in Virtual GIS for pop-up menus that are used just like the menus in a 2D interface. Thus it is as if the user is looking at the 3D scene through a transparent desktop. Menu selections are made with the 3D mouse cursor motion projected onto this desktop plane, acting just like a 2D mouse interface. In general we have found that this is the easiest way for users to make menu selections in the immersive virtual environment, given the current accuracy of trackers and the current resolution of the HMD. This notion is backed up by motion control experiments that we have made and will report on soon.

2.1 DATASETS

Each dataset used with Virtual GIS may contain several types of information. Terrain surfaces are visualized as a mesh of shaded or textured polygons. Additional non-protruding features may be overlaid on the surface, such as graphical representations of roads and waterways. Protruding features include individual trees and buildings. Animated vehicles may also be included in the datasets.

The topography of the terrain model in a Virtual GIS dataset is represented by a rectangular, uniform grid of elevation points. Overlaying the mesh of elevation points with phototexture aerial photo imagery provides a highly realistic appearance and a variety of information. High resolution phototextures allow easy identification of visible features such as roadways and foliage variations. GIS raster layer data corresponding to the terrain area may also be included in a dataset. Information such as soil type, road surface, or foliage density can be stored in these GIS layers and be rendered or queried.

Trees in Virtual GIS datasets are represented so as to have a realistic appearance, while maintaining a simple data structure to allow inexpensive storage and quick rendering. Each tree is represented as a single rectangular polygon, with a realistic phototexture applied. Each tree polygon is rotated about its trunk axis each rendering frame so as to always be facing the eyepoint of the user.

Other protruding features in Virtual GIS are represented using the hierarchical object structure supported in the SVE toolkit. SVE objects are specified using polygonal primitives very similar to other common graphical object definition formats. Features implemented this way in Virtual GIS datasets include buildings and vehicles. Objects may also have additional animation information associated with them, which describes a path of control points the object is to follow, along with other animation data such as start and stop times, speed, and motion characteristics.

For the purposes of showing capability with widely different terrains, we have prepared databases for both open country and urban settings. For the open country we use a dataset of interest to the Army representing an 8 km x 8 km section of Fort Hunter Liggett in California, with a maximum terrain resolution of 2 meters. For the urban setting we use a database of the Georgia Tech campus, an area of about one square mile, at a maximum resolution of 4.9 feet. Both datasets also include geographical information databases as well as models of trees, buildings, and vehicles. Thus we have for our use two large, realistic datasets, the former emphasizing terrain features such as mountains, hills, and waterways, and the latter emphasizing the number of buildings and other objects.

2.2 SYSTEM FEATURES

Users of Virtual GIS are allowed complete freedom in navigating about the virtual world described by the databases. Both the window-based and immersive interfaces allow flight through six degrees of freedom (pitch, yaw, roll, and three-dimensional translation). In addition to the free flight capability of Virtual GIS, a number of other system features may be accessed through the popup menu system.

2.2.1 NAVIGATION

Past experience has shown that users of virtual environments are vulnerable to getting "lost" and disoriented in the virtual world. A number of navigation techniques have been proposed to alleviate this effect and aid understanding of the virtual environment [4]. The Virtual GIS system implements two methods. First, the user can toggle a labeled coordinate grid system overlaid on the terrain. Additionally, the user can turn on a popup inset overview map, complete with markers showing the position of the user and other significant objects in the environment. Figure 1 shows an aerial photo overview map inset in the upper lefthand corner of the display.

As an alternative to flying through the Virtual GIS environment, the user may jump directly to any point in the world. The user can select a point either on the visible terrain, or on the overview map, and instantly jump to that location, while maintaining the same distance above the terrain surface. Another option allows the user to jump back to their previous location.

Movement about the environment can be constrained in a number of ways. Collision detection with the terrain surface has been implemented to prevent users from flying beneath the modeled portion of the dataset. Users have the option of moving about the terrain at a fixed elevation above the surface, in order to experience the terrain features. Also, users may attach their viewpoint to objects in the environment. Attaching their viewpoint to an animated vehicle, for example, allows the user to ride the vehicle through the terrain on its pre-assigned route. Figures 2 and 3 show the viewpoint attached to a moving tank and helicopter, respectively.

2.2.2 QUERY

The Virtual GIS system provides a unique visual interface to a variety of geographical information. Users of the system can access this database by directly querying objects in the virtual environment. For example, clicking on a building object in the environment may display the name of the building, or bring up an image showing the floor plan of the building. Similarly, the user can select any point on the visible terrain. If any GIS raster data layers are active for the virtual world, then the appropriate data label will be displayed, along with the corresponding coordinates of the selected point.

2.2.3 RENDER OPTIONS

Users of Virtual GIS are afforded significant control over what features in the environment are rendered. Roads, waterways, trees, buildings, and military units can be individually displayed or hidden. The terrain can be rendered in three different modes. In one mode, only a wireframe representation of the terrain and objects is displayed. In the shaded rendering mode, the terrain is rendered in a single color, using Gouraud shading to highlight terrain contours. Figure 4 shows the system in Gouraud shaded mode, with the user making a GIS data query through the popup menu system. In the default textured mode, the terrain is rendered with phototexture imagery applied to the terrain polygons.

2.2.4 SPECIAL EFFECTS

Virtual GIS offers a number of additional visualization options. Haze can be toggled on and off by the user, and haze parameters such as density and color may be specified. When using the shaded terrain rendering mode, the virtual sun position may be changed to simulate lighting conditions at a specified time of day. Animation scripts can be executed, which coordinate sequences of object motion.

2.3 HIERARCHICAL, MULTI-RESOLUTION DATABASE REPRESENTATION

The Virtual GIS system is designed to display terrain databases extending over large areas, at high resolutions. Dealing with such large, complex databases requires special data structures and algorithms to keep the system running at interactive rates (at least 15 rendering frames per second, to meet our "real-time" criteria). A terrain model with area eight kilometers by eight kilometers with elevation and phototexture resolution of four meters requires 8,388,606 triangular polygons and 12,582,912 bytes of phototexture data. This level of complexity easily exceeds the rendering capacity of most graphics hardware.

The Virtual GIS system handles complex terrain models by culling areas outside of the field of view, and by using level of detail reduction of the terrain data [5]. Both of these techniques are facilitated by a "quadtree" hierarchical internal representation of the terrain model [6]. The top level node in this tree represents the area of the entire database, and each child in the quadtree represents one fourth the terrain area of its parent. Each node in the tree corresponds to a block of terrain with the same number of data points. The highest resolution data blocks belong to the deepest level of the tree.

The quadtree representation allows for efficient polygon culling. By intersecting the terrain with the user's viewing frustum, terrain blocks outside of the field of view can be culled away, reducing the number of polygons that actually need to be rendered. The hierarchical structure of the quadtree allows for culling of large terrain blocks at the top levels of the tree. For a field of view of 90 degrees, the culling stage generally reduces the number of polygons to be rendered by more than half.

Further reduction in the complexity of the terrain model is achieved through level of detail management. Level of detail algorithms are applied to reduce the number of polygons rendered, as well as to reduce the amount of texture data required at any one time (many graphics workstations have limited texture memory caches).

The complexity of the terrain polygon mesh is reduced based on three criteria: distance from the viewer, angle with the view vector, and roughness of the terrain. The appropriate data resolution for each visible node in the quadtree is evaluated according to these criteria. Regions of the terrain that are far away from the user's viewpoint, or that are relatively flat, will be rendered with lower resolution data. Similarly, if the user is looking perpendicular to the slope of a terrain section, lower resolution data can be used without any significant difference in the rendered image.

Multiple phototexture resolutions are used for each node of the quadtree as well. Two criteria are evaluated for determining appropriate phototexture resolution: distance from the viewer, and angle with the view vector. The number of screen pixels occupied by a terrain mesh polygon decreases as the polygon gets further away from the viewpoint, and as the polygon is rotated away from the viewer. Less phototexture pixels (texels) are then required to achieve the same final rendered image quality. For many areas of the terrain, then, lower resolution texture data can be used.

Figure 5 shows an example of the rendered terrain both with and without level of detail processing. The lower complexity model is almost indistinguishable from the full resolution rendering. Empirical testing has shown that the techniques used by Virtual GIS for level of detail management provide two orders-of-magnitude reduction in the number of polygons rendered, and a one order-of-magnitude reduction in the number of bytes required for texture memory. The computational cost of these algorithms is relatively insignificant.

Techniques are also implemented to optimize rendering of protruding objects in Virtual GIS datasets. Trees are included in the terrain quadtree representation to allow hierarchical culling of trees outside of the viewing frustum. The SVE toolkit provides mechanisms for culling buildings and other objects in the virtual world, as well as multiple level of detail rendering based on distance from the viewpoint. These methods, along with the specialized terrain rendering algorithms, allow highly complex datasets to be rendered at interactive rates. The Virtual GIS system typically operates between fifteen and twenty frames per second on our sample datasets, using a Silicon Graphics Crimson or Onyx with Reality Engine graphics.

3. FEEDBACK FROM REAL USERS

Testing of any visualization system by potential user groups is a necessity. The current implementation of the Virtual GIS system has been used in actual field exercises of the U.S. Army. A dataset for the National Training Center at Fort Irwin, California was prepared, and soldiers used the system to visualize the topography of the terrain around their operating areas. Unit commanders were able to indicate placements of their sub-units on the terrain model, so that the sub-unit commanders could easily visualize their ordered positions. Testing of the system by real users provided significant feedback that is being used to improve the system design. For example, the soldiers found the six degree-of-freedom window-based steering interface difficult to use. They requested additional navigation features, such as a directional compass to aid orientation, and the ability to jump to a location specified directly by inputting map grid coordinates. We are currently implementing these and several other suggested features into the Virtual GIS system.

The Army users also determined that the 30 meter resolution National Training Center dataset was not sufficient for accurate military planning purposes. Due to the resolution of the objects they operate with, data up to one meter resolution is required. The demands of such high resolution datasets is shaping future development of Virtual GIS.

4. RELATED WORK

Many researchers have examined issues related to the integration of visualization techniques and GIS [10,11].

Several 3D GIS systems have been implemented [12], although none provide for the real-time rendering of the variety of high resolution datasets like those used with Virtual GIS.

Increasing attention and development has been addressed recently to systems allowing real-time visualization of terrain datasets. The NPSNET system [13] has evolved from a military vehicle simulator into a large scale, distributed virtual environment system for military simulation and training. NASA's Virtual Planetary Exploration project [14] supported virtual exploration of planetary terrains in real-time. The TerraVision system [15] is described to implement some of the terrain visualization functionality of Virtual GIS, using similar data structures and algorithms to support real-time rendering.

5. FUTURE WORK

Our goal is to be able to quickly navigate a model of the world, choose a country or region and obtain a 3D terrain and feature map, choose a subregion for closer inspection, and then bring up a real-time 3D visualization of that subregion with access to a GIS database and with up to date information such as military units and features. Such a goal requires the ability to query a variety of information servers, quickly transfer possibly large amounts of data with varying formats, amass these data and organize them into a hierarchical data structure for real-time navigation, and then perform callbacks to the servers or directly to data collection devices to provide new events or updates.

Our approach to reach this goal depends on a heterogeneous, tightly coupled distributed system consisting of database servers, a set of high speed processing units for parallel computation and I/O, and the functionality of our current Virtual GIS system for real-time rendering and interaction. For our Army application, database servers containing terrain, features, units, control measures, and weather information will be queried by the intermediate, parallel system. This system will collect, reformat, and structure the data, and pass it on over a high-speed network connection to a rendering engine with pipelined graphics and capability for low-latency, real-time control and interaction. A second network connection from the rendering engine back to the parallel computation system will carry commands to enable staging and sending of the next set of data for rendering.

We are currently implementing paging algorithms which allow arbitrarily large terrain datasets to be stored on the local disk of the graphics workstation. As the user moves about the virtual world, new data from the disk is dynamically loaded into the quadtree structure and rendered, and data for regions no longer in the area of interest is discarded. We are developing a tunable, adaptive rendering management model such as those described in [7,8], which takes into account system load functions, user interest weight functions, and other factors, to provide a system that meets interactive performance requirements while maximizing fidelity of the visualization data.

In addition to our data paging and remote server extensions to the Virtual GIS system, we are developing a 3D symbology adequate for the task of displaying and making sense of large amounts of constantly changing data from several sources. The user must take in the information conveyed by these 3D symbols (or glyphs) at a glance, must be able to see the structural and functional relations between them (whether the objects represent the same or different classes of data), and must be able to grasp time-dependent behavior. In addition, the 3D symbology must be related to a well-established and extensively used 2D symbology; we will use the Army's own collection of 2D battlefield symbols to make this connection [16]. We will base our approach on methods we have previously developed, which are well-suited to presenting several time-dependent variables simultaneously [9].

6. CONCLUSIONS

Virtual GIS is a highly integrated, efficient real-time 3D GIS for visualizing geographical data. The system features an immersive interface, significant visualization and GIS functionality, and provides sophisticated management of the large, complex datasets typical of geographical data. Functional integration of visualization and GIS technologies has been a goal of researchers in both of these areas. The Virtual GIS system demonstrates that these two technologies can be successfully combined.

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