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Research Article

An integration of GIS, virtual reality and the Internet for visualization, analysis and exploration of spatial data

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Abstract. This paper explores the way in which GIS, Virtual Reality (VR) and the Internet are closely integrated through the link of Virtual Reality Modelling Language (VRML) for spatial data visualization, analysis and exploration. Integration takes advantage of each component, and enables the dynamic 3D content to be built, visualized, interacted with and deployed all on the Web. To accomplish this, a hybrid approach that merges the conventional client-side and server-side methods is proposed, which offers the best of both worlds in terms of flexibility and capability, as well as the rational use of computing resources. Based on this approach, a Web-based prototype toolkit is designed and implemented by using an affordable desktop GIS through its macro language together with Java, Common Gateway Interface (CGI) and HTML programming. This toolkit comprises a 3D visualization tool, a 3D analysis tool, and a Java/VRML interface, which are respectively used for the creation of VRML models from 2D maps, surface analysis (e.g. profile creation and visibility analysis), and interaction (e.g. selecting and querying) with the output VRML worlds of 3D visualization and analysis. It is demonstrated that this toolkit provides an integrated environment, facilitating users to gain insights from the interaction with virtual environments that are built from existing GIS databases.

1. Introduction

Over the past decades, large volumes of digital spatial data have been created using geographical information system (GIS), computer-aided design (CAD), and image processing systems. The need to visualize and explore these data is becoming widely recognized (Rhyne 1997, Kraak and MacEachren 1999). At the same time, there is also a strong incentive to distribute the result efficiently.

The advent of Virtual Reality (VR) technology and the Internet has provided opportunities to satisfy these needs, as they are two important means for data representation, interaction and dissemination (Batty *et al.* 1998). The Internet, in particular, the World Wide Web (WWW), has experienced an astonishing growth in recent years, and the Web is now been widely used as a distributed computing environment. The GIS community has embraced this, and there is an increasing field of Internet GIS (or Web GIS) (Plewe 1997). However, current Internet GIS is still

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limited to map display and simple graphic manipulations such as zooming and panning. It lacks 3D visualization and interaction capabilities. VR, allowing for more realism in the portrayal of geographical phenomena (Smith 1997), can play a significant role in making up this. On the other hand, geographical VR applications also need the support of spatial analytical functions, which could be provided by a GIS. As a result, there is a clear requirement for the integration of GIS, VR and the Internet to complement and enhance each other to facilitate the exploration of spatial databases.

The integration of GIS, VR and the Internet are made possible through the use of Virtual Reality Modelling Language (VRML), an ISO standard for describing interactive 3D objects and worlds to be experienced on the WWW (Carey and Bell 1997). It is the existence of this standard and the widespread availability of VRML plug-ins, which makes Web-based 3D visualization feasible (Brodlie and Wood 2000). Through VRML, in conjunction with Java and HTML, GIS, VR and the Internet can be combined in different ways to support Web-based modelling, visualization and analysis. This is reflected in various VR applications in urban environments and the 3D city-scape (Martin and Higgs 1997, Fairbairn and Parsley 1997, Doyle *et al.* 1998). Arising from these applications, a number of GIS-VR prototypes have also been implemented. The integration of GIS, VR and the Internet has been attempted in one way or the other, but there is still lack of a systematic investigation, which analyzes different integration strategies. In particular an appropriate approach for the efficient and effective integration needs to be addressed.

This paper reports on our research oriented towards the full integration of GIS, VR and the Internet. While previous integration of VRML and GIS primarily took a loose coupling approach, we seek a tight coupling. Current Internet GIS deploys data and software to either the client-side or the server-side, causing a seriously unbalanced utilization of computing resources on the client and server sides. To overcome this problem, we propose a hybrid approach, which combines the advantages of both client- and server-side solutions, and thus is considered ideal for the organization of visualization and analysis tasks. Based on this hybrid approach, a prototype toolkit is designed to provide an integrated environment, where users can carry out interactive 3D visualization and analysis on existing GIS databases, and interact with the corresponding results, whether in 2D map/graph or 3D VRML form, on the Web. The selected 3D analysis functions are the commonly used ones but in a different setting. These functions include profile creation and visibility analysis. The primary objective in exploring data in 3D is based on the idea that 3D space may offer insight that might otherwise go unobservable, as humans are better able to relate to and understand 3D space. This toolkit is implemented by using off-the-shelf GIS software through its macro language as well as Java and HTML programming.

The remainder of this paper is organized as follows. Section 2 presents relevant technologies such as GIS, VR, the Internet and their possible integration, and provides a comprehensive review of the related work. Section 3 addresses a hybrid approach for the seamless integration which merges client- and server-side solutions for Internet computation. Section 4 gives an overview of the implementation of the prototype toolkit based on the hybrid approach. Section 5 illustrates a range of exploratory functions of the implementation towards a full integration of GIS, VR and the Internet. Finally §6 concludes the paper and points out future work.

2. GIS, VR and the internet: towards a full integration

The definitions of GIS, VR and the Internet appear self-explanatory. It is, however, still necessary to define these terms in this context, in order to make it clear what we mean precisely by these terms. GIS can be defined as a spatial data processing system with three important components: spatial database, analytical functionality, and visualization capability. However existing GIS is mainly 2D based, though there is a high demand for 3D visualization and analysis. VR is a computer graphic technology that can be used to emulate the real world in three dimensions, with which users can participate in the virtual environment by walking or flying. In terms of interaction with virtual environments internally or externally (MacEachren *et al.* 1999), we can have distinction between immersive or non-immersive VR. We employed desktop VR, a kind of non-immersive VR, in this study as it is increasingly used in the context of GIS and online mapping. The Internet is a network with millions of computers interconnected through various forms of telecommunications, providing infrastructure for information dissemination.

Given these definitions of GIS, VR and the Internet, a number of integration approaches are possible (figure 1):

Internet GIS: Internet GIS is the combination of the Internet and GIS, that is, a conventional GIS using the Internet as a basic information infrastructure for spatial data dissemination. Because of the nature of the Internet, Internet GIS is regarded as an interactive, distributed, dynamic, cross-platform and client/server computing system, and it has the capability to access various forms of GIS data and functions in an interoperatable environment (Plewe 1997, Peng 1999).

VRGIS: VRGIS is used to represent the combination of VR and GIS technologies, that is, a conventional GIS with VR as the main interface and interaction method (Faust 1995, Raper *et al.* 1999). Because VR provides a rather realistic representation of the world, it can be a nice complementary tool for existing GIS. VRGIS has

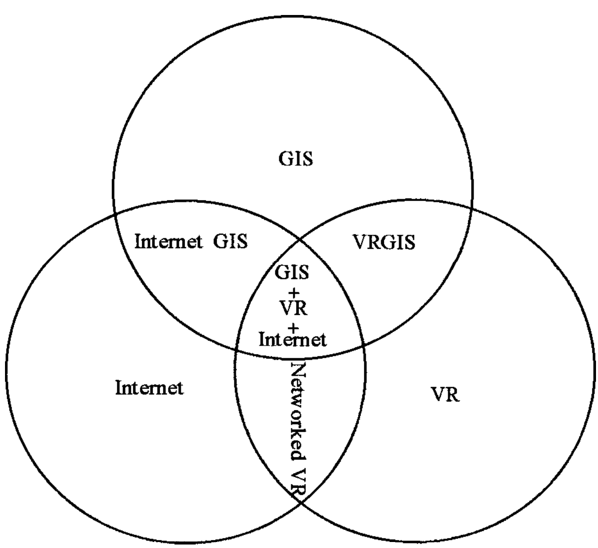

Figure 1. GIS, VR, Internet and their integrations.

been widely used in urban and environmental planning, scientific visualization, archaeological modelling, education and military simulation.

Networked VR: Before the Internet was made available, VR models were stand-alone like CAD models. Nowadays with the development of the Internet technology, these VR models can be networked, and participants can be involved in VR by logging in a network computer. A typical example is ActiveWorlds which has received increasing attention in the field of education, film-making and urban planning (ActiveWorlds 1999). Users can interact with VRML worlds on the Internet by using the Java language. Some examples in the context of geographical applications can be found in Brown (1999) and Moore *et al.* (1999). More details about networked VR and associated techniques are given by Singhal and Zyda (1999).

A full integration of these three provides many advantages for setting up a platform for distributed spatial decision-making. In such an integration, GIS provides rather rich spatial data, VR helps to visualize the large volume of data in a rather realistic format, and the Internet facilitates information dissemination. Taking an example urban planning and design, a GIS or CAD package can be used to finish a 2D sketch plan, and VR used to create a 3D urban scene from the 2D map or plan, and the Internet used to facilitate public assessment by putting the VR model online. The above processes can continue recursively until a final design is agreed upon. The process may involve some analysis and geocomputation that are important to decision making.

Much effort has been focused over the past years on Internet GIS, VRGIS and Networked VR from a variety of disciplines. Early work involved urban simulation using higher-end computer facilities. These developments took place on stand-alone platforms as the Internet was not then conceived. The earliest work dates back to the 1970s, when several pilot projects were developed at the Graduate School of Architecture and Urban Planning at the University of California at Los Angeles (UCLA). Let us put the related work at two different categories: before the Internet when GIS (CAD) databases are considered as a data source of VR, and after the Internet when networked VR is considered as a visualization function of GIS (figure 2).

Before the Internet was made public, much work has been done in order to integrate VR and GIS for various purposes such as urban simulation (Ligget and Jepson 1995, Radford and Day 1996), and urban and landscape planning (Shiffer 1992, Bishop *et al.* 1995). Within these efforts, GIS/CAD provides an important data source for VR models. Thus GIS can be considered as a part of VR.

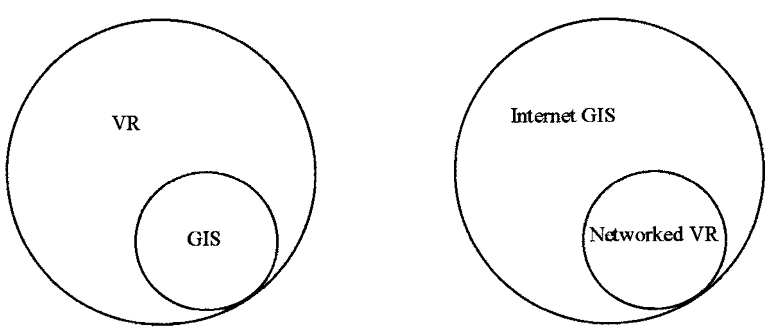

Figure 2. Integration of GIS and VR: current practices.

As desktop VR and the Internet have gained some popularity, a number of projects have been carried out to incorporate VR and the Internet into the GIS environment. Under the banner of new technologies for urban designers, the VENUE (Virtual Environments for Urban Environments) project was set up which aimed to develop a suite of computer tools for urban planners and designers using GIS, VR and the Internet technologies (Jiang *et al.* 1997, Batty *et al.* 1999). Within that project, various tools have been developed for modelling urban environments (Doyle *et al.* 1998). Another ambitious project is the VFC (Dykes *et al.* 1999b), which aims to develop virtual environments to facilitate student fieldwork. Many other projects have also been carried out. For example, Verbree *et al.* (1999) built a VRML interface for modelling, manipulation and editing of spatial worlds, which demonstrated an approach for real 3D GIS operations. Kahkonen *et al.* (1999) demonstrated work on the development of NetGIS in line with Common Object Request Broker Architecture (CORBA, OMG 1998) and other relevant standards for spatial object browsing and interrogation. In this tool, an established VRML file can be linked with a spatial object and viewed with a VRML browser upon request.

The effort in applying VR as a useful function of GIS is not limited to academics, the commercial company and private sector have also made a rapid response to the development. The most distinguished development in this connection is VRML, which has gained more acceptance as a technology for displaying 3D graphics as it is a simple and accessible way to create interactive worlds. The release of VRML has also been a major factor in the uptake of VR in the geographical field (Moore *et al.* 1999). This is due to the fact that since its inception, VRML has been employed for more realistic and interactive representation of geographical data such as terrain models and city blocks (Dykes *et al.* 1999a). Some socio-economic information has also been explored in a rather realistic way through VRML models (Martin and Higgs 1997). Furthermore, GeoVRML, an extension of VRML, has been proposed and implemented to provide geoscientists with a suite of enabling functions for the representation of large volume and high precision georeferenced data. Recent advances in GeoVRML include a number of new nodes that enable the transparent and accurate representation of geographical data, and support scalability to large spatial databases; see (Rhyne 1999) and (Reddy *et al.* 2000) for more details.

Some commercial VR tools have also been made available. Pavan (Smith 1997), VirtualGIS (Schill 1999), and ArcView 3D analyst (ESRI Inc. 1997b) are three typical examples with respect to the creation of 3D VRML models from GIS data. Pavan is a VRML compiler and project management system for the MapInfo GIS. It can create generate navigable 3D (VR) models generated from data held in MapInfo. The resulting models can be represented by VRML and viewed interactively in most recent versions of Web Browsers. VirtualGIS is an add-on application for 3D visualization and analysis to ERDAS Inc.'s IMAGINE Essentials, and has similar functions to Pavan. ArcView 3D analyst also has similar functions, and will be introduced later in §4.1. Obviously, in these three packages, the process of VRML model generation is not conducted on the Internet, and is loosely connected with the process of VRML model browsing. In other words, these packages are still desktop tools. Rather than the loose coupling of GIS, VR and the Internet, we will concentrate on the exploration of a tight coupling to provide an integrated environment for more comprehensive spatial data visualization, analysis and interaction: full and seamless integration.

3. A hybrid approach to merging client- and server-side applications

As the Internet has become an important means for acquiring and disseminating information, a number of Internet GIS products have been brought to market. Underlying these products, there are two basic approaches to deploying GIS or any other complex, data driven applications on the Internet: server-side and client-side applications. The former approach depends on the GIS server to perform all processing tasks and sends the results to the front-end upon clients' request, while the latter approach allows the data and software to be transferred to the local client side and executes all processing at the front-end (Plewe 1997, Gifford 1999, Peng 1999). The following discusses the features of each approach as summarized in table 1, and then derives a hybrid approach for the full integration of GIS, VR and the Internet.

The server-side applications, having main software and databases on the server side that link with the Web server through a Common Gateway Interface (CGI) script, significantly simplify development, deployment and maintenance of the Internet GIS software. The application software on the server side can be proprietary, but the results transmitted to a Web client are in standard HTML formats that can be viewed in any Web browser, creating significant positive implications for performance, reliability and size of user base. This is also beneficial to the incorporation of different functionalities into the application server. Disadvantages of server-side solutions are associated with limited user interface and poor performance. Basic map operations such as zooming and querying also require a new request to the server and returned. This results in many requests, possibly causing an over-loaded server.

Client-side solutions typically are implemented by augmenting the Web browser in the form of plug-ins, ActiveX or Java. Plug-ins are software modules that apply to specific file-types when a Webpage is loaded. They are used to perform basic operations such as zooming and panning within a Web browser, thus easing the over-loaded server. But plug-ins are native to a specific platform on which the Web browser runs, and require download and installation in advance, which is not convenient for a casual user. Numerous plug-ins mixed in a Web browser may also result in the paralysis of the browser. Active X controls are similar to plug-ins (Peng

Table 1. A comparison of client- and server-side applications.

	Server-side solution	Client-side solution (Java-based)
Advantages	Can adhere to all Internet/Web standards	Modern GUI and flexible interaction
	Can utilize existing GIS functions	Vector data can be used
	Centralizes administration of data and GIS application software	Good performance for operations that occur locally
	User support minimal	Less Internet traffic
	Comparatively mature and simple	Not restricted to Internet document/graphics standards
		Can be installed on demand, no permanent disk space is used
Disadvantages	Poor interface	Time consuming for downloading data and software
	Lack of interactivity	
	Creates many requests	Difficult for complex data processing

1999), but can only be applicable within the MicroSoft's Internet Explorer environment. By contrast, the use of Java is considered to be the most flexible and futuristic method because the coded software can potentially achieve platform-independence, and can possess such powerful programming functions as any other advanced languages like C. A Java applet also allows the use of vector data structures for graphic data display and processing. In general, the primary advantages of client-side solutions are the abilities to enhance the user interface and improve performance. But downloading the software and data to the client may be time-consuming, and the complex data processing functions may not be as efficient as those in a powerful server.

In summation, both client- and server-side methods have pros and cons, and the use of either of them is not adequate for a wide range of GIS applications on the Internet. In effect, the comparison of them suggests that both methods be considered complementary rather than competitive. Hence the integration of client- and server-side solutions, typically in the form of Java and CGI, is taken as a better approach. Such a hybrid approach can significantly benefit from the strengths of each, because it can provide not only a user-friendly interface by use of Java but also a powerful data processing server by use of CGI-linked existing GIS functionalities.

The use of the hybrid approach can allocate different tasks to the appropriate side for workload balancing. Rather than the simple use of both sides, there is a sharing of responsibility between the client and server sides, allowing for true client/server interaction. This is the core of the hybrid approach *per se*. In general, complex spatial data processing tasks (e.g. VRML model generation) are performed on the server side, while user interaction and system control tasks are carried out on the client side. Basic map operations such as zooming and feature selection no longer require a round trip to the server side as done in the CGI approach, but are handled locally, yielding quick and efficient performance. Network traffic is reduced as well.

For these reasons, the hybrid approach fits in with the various requirements of Web-based spatial data exploration under study in this paper, which involves 2D data visualization, 3D VRML model generation, 3D surface analysis and VRML interaction with respect to not only complicated visualization and analysis tasks, but also flexible interaction for adjusting parameters or retrieving information.

4. Prototype implementation

The prototype toolkit, GeoV&A, is designed to serve as a testbed for the hybrid approach. Its implementation is on the basis of the desktop GIS ArcView together with Internet techniques such as Java, CGI and HTML. The server part of the toolkit has been made into an extension, which is similar to other ArcView extensions such as spatial analyst and network analyst. After checking that this extension is on, users just need to choose a Web server and connect it with the V&A (Visualization and Analysis) server, then this visualization server can provide services to the client across the Internet.

4.1. *Software support*

ArcView is a desktop GIS with components including spatial view, table, chart, layout and script. Each of these serves different purposes for spatial data processing and presentation. Among others, of importance is Avenue script (an object-oriented language) which permits the customization of the ArcView interface, and provides some additional spatial functions. Avenue contains useful built-in classes for graphics manipulation, spatial queries, and basic arithmetic calculations. GeoV&A has been designed as a specific graphic environment by modifying existing ArcView controls (menus, menu items, buttons and tools), and linking relevant scripts with new controls created.

ArcView has a set of extensions such as Internet Map Server (IMS; ESRI 1997a) and 3D Analyst (ESRI 1997b). As an extension, IMS enables users to put maps and interactive mapping applications on the Web. A user can employ this extension to provide information services based on dynamic maps and GIS data. The 3D Analyst extension allows users to create, analyze, and display surface data. It, however, has not been accomplished on the Internet. This paper reports on our experiments in this regard.

Besides the above, a VRML plug-in called WorldView (http://www.intervista.com) is used to view the output VRML scenes within a Web browser. VRML browsers which are largely free software enable a user to interact with a virtual world via scaling, zooming, rotation, etc. in three dimensions. In addition, the Java programming language is employed to design all the interfaces of GeoV&A. Java is also flexible for creating and displaying graphics and maps and thus is appropriate for the manipulation of GIS data across the Web.

4.2. *The architecture of GeoV&A*

The client/server architecture of GeoV&A is designed in the light of the hybrid approach. It has a typical three-tier configuration (figure 3):

- A Java-based client residing with the Web browser: Internet Explorer or Netscape Navigator.
- A Web server (e.g., Microsoft Personal Web Server for Windows NT Workstation) with an ESRIMap extension in ArcView IMS.
- A 3D visualization and analysis server (V&A server), i.e., an application server using ArcView and its 3D extension via Avenue programming.

The client side of GeoV&A provides several Webpages embedded with Java applets, which allow users to select operations, define properties of 3D scenes or input parameters for 3D analysis. A user then submits the request in the form of

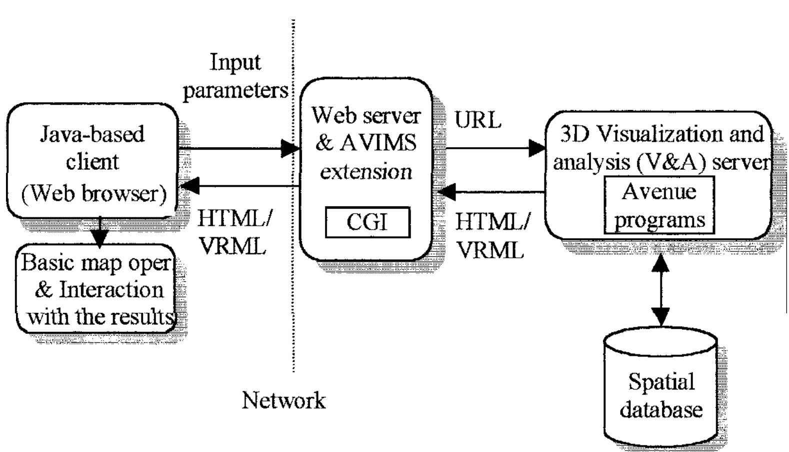

Figure 3. Three tier client/server architecture of GeoV&A.

Unique Resource Locator (URL) to the V&A server via a CGI program within ArcView IMS running on the Web server, or conduct some operations (e.g. 2D map browsing) locally. The correctness of parameters is also examined by the Java-based client before a command is submitted. The main mechanism for Java-based clients in GeoV&A to communicate with the V&A server is through the encoding of parameters in URL. After receiving a URL request from the Java-based client, the V&A application server extracts all the necessary parameters, processes them, and then delivers the results in HTML-compatible format to the client for display. The results could be a 2D map (§5.2.2) or a 3D VRML model. In both cases, users can still interact with them via zooming, panning, and querying on the client side.

5. An illustration: the basic functions of GeoV&A

GeoV&A has four main modules: 2D visualization, 3D visualization, 3D analysis and VRML interaction (figure 4). Some results of 3D visualization and analysis are sent to the 2D visualization module, and the others are sent to the VRML interaction module for further processing. These modules are interconnected, providing an integrated environment for spatial data visualization, analysis and interaction in 2D and 3D.

The main user interface of GeoV&A is shown in figure 5, which is the first Webpage a user encounters. This Webpage provides two buttons, where users can select either 3D visualization or 3D analysis functions. Then, different Webpages are presented for further running of the software. After a series of operations, users can still go back to this interface for further visualization or analysis. Note that the 2D visualization functionality is described within the 3D visualization part, but the VRML interaction functionality is described in a separate.

We use a data set from ESRI within the 3D Analyst package for the illustration. This data set includes two shape files (a building file and a road file), a TIN (Triangulated Irregular Network) and a GRID terrain surface files, and an ortho-photo image file. All these files can be read by ArcView and the Java applets we developed.

5.1. *3D visualization*

The 3D visualization in GeoV&A serves to create 3D perspective displays by extruding spatial features in 2D GIS maps. Attributes of spatial features (e.g. stories

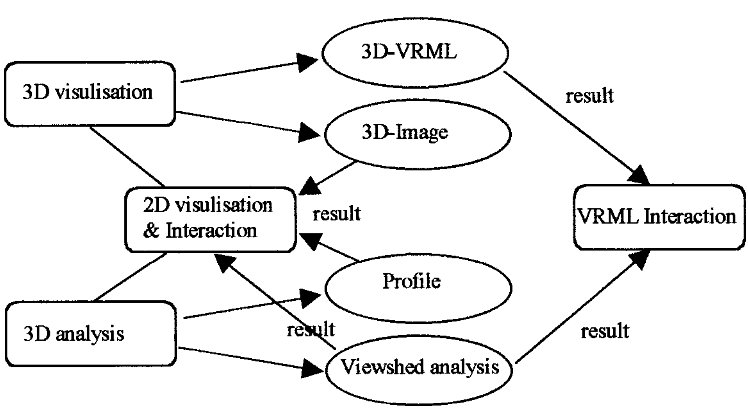

Figure 4. Functionality of GeoV&A.

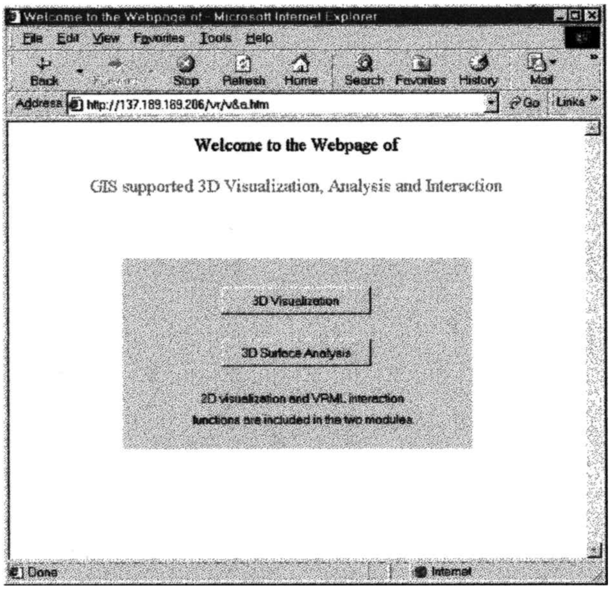

Figure 5. The starting interface of GeoV&A.

of buildings) are usually taken for height information (Z-value). Such an extrusion changes the form of a feature: points into vertical lines, lines into vertical walls, and polygons into 3D blocks.

Like the example shown in figure 6, the user first begins with the parameter input and selection page. This Webpage comprises several items including 2D theme, spatial feature extrusion height, base height and others. Once the 2D theme is

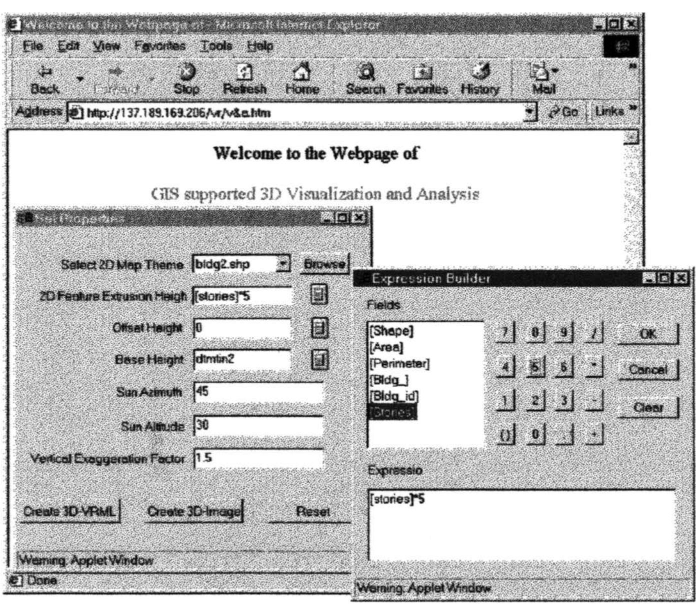

Figure 6. Parameters input for creating a 3D scene in the form of VRML or image.

selected, it can be browsed without the input of other parameters. The item of 2D feature extrusion height allows users to give height information (Z-value) in the form of a value or an expression to the spatial features in the selected 2D theme. If the height information is in the form of an expression, the right button of the item textbox can be invoked to pop up an expression builder dialogue, which assists users in the formulation of the expression. Similarly, offset height and base height can also be entered in this way. The base height item can also be a TIN or GRID surface file. Sun azimuth and altitude define the sun position for shading, and the vertical exaggeration factor scales up the height for the 3D scene to be generated.

In addition to the above items, there are four functional buttons: 'Browse', 'Create 3D-VRML', 'Create 3D-Image', and 'Reset'. The 'Browse' button is chosen to browse the selected 2D theme. Figure 7 shows a Java window which displays the 'bldg2.shp' map in the vector file format. By clicking one of the four 'radio' buttons above the 2D map, the user can pan, zoom in, zoom out or identify a feature in the map. The 'identify' option is employed to show the attributes of a selected feature. Note that all these basic map operations are conducted locally within a Java applet, which do not require any processing by the V&A server. This applet can also display image files.

The 'Create 3D-VRML' function serves to generate a 3D scene and its VRML model on the fly. After receiving a URL request from the Java-based client, an Avenue script first extracts the parameters for assigning feature height, base height, offset height, sun azimuth and altitude, and vertical exaggeration from the URL, it then generates a 3D scene by using these parameters. Finally the 3D scene is transformed into a VRML file (with .wrl extension). The VRML nodes used here are mainly IndexedFaceSet and ElevationGrid. For more details of these nodes see (Moore *et al.* 1999). Meanwhile, a legend in GIF image file format for the VRML model is also created, which helps users interpret the model on the Internet. Both the VRML and legend files are linked to an HTML file and sent back to the Web browser for display.

By using a WorldView plug-in that has already been established on the Web browser, the VRML model can then be navigated. Figure 8 shows the result as to the input in figure 6, where buildings are placed on top of the terrain model. In figure 9, a VRML model of an orthophoto image draped over the terrain surface is shown.

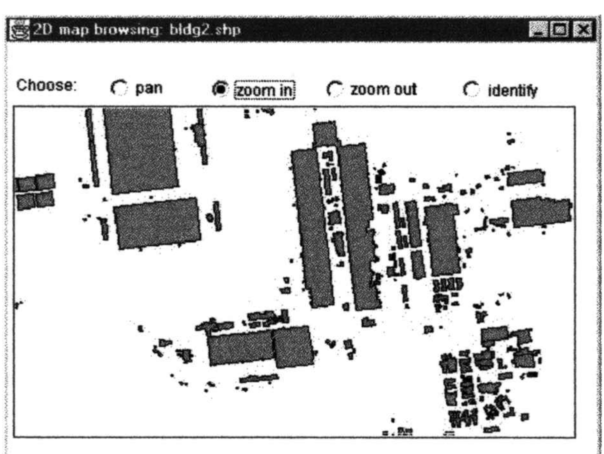

Figure 7. Identifying a selected feature when browsing the selected 2D map.

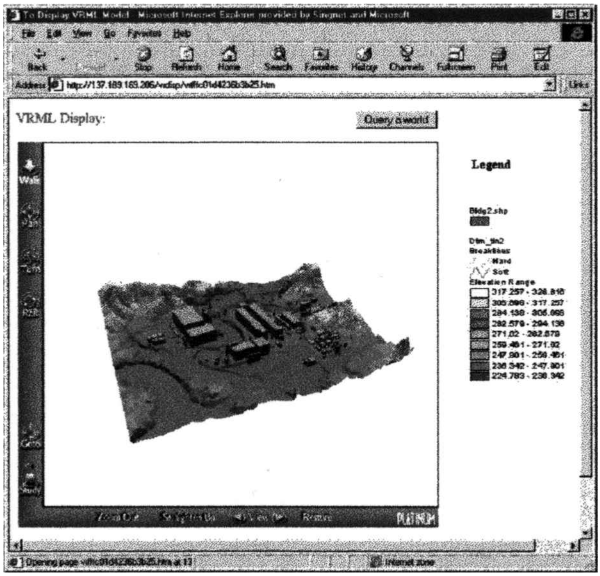

Figure 8. A VRML presentation of buildings on top of the terrain surface.

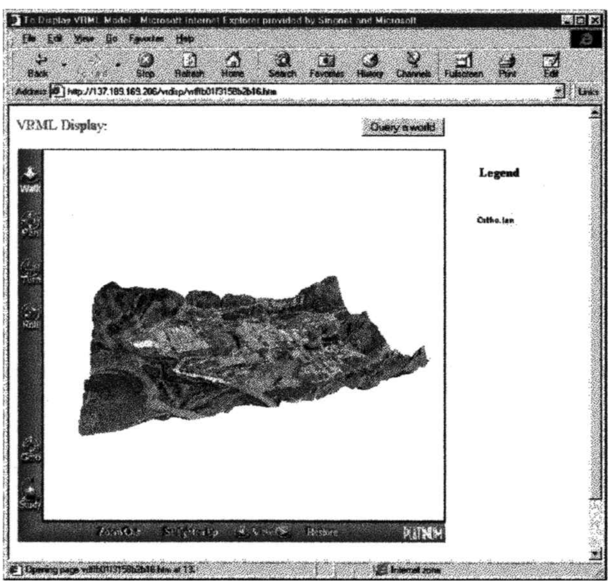

Figure 9. A VRML presentation of an orthophoto draping over the terrain surface.

Unlike the 'Create 3D-VRML' function, 'Create 3D-Image' function creates an image of the generated 3D scene for a quick look. Finally the 'Reset' function is used to define all the parameters with their default values.

5.2. *3D analysis*

Terrain surfaces are frequently used in many types of geographical analysis such as suitability studies, hydrologic analysis, visibility analysis, and more. Other kinds of surfaces, such as population density and average rainfall are employed in other types of analysis. Since so many phenomena are principally made up of surfaces, analysing those surfaces is obviously an efficient way to understand the phenomena.

GIS surface analysis functions usually include slope and aspect calculations, volumetric calculations, contouring, profiling, and visibility analysis. GeoV&A provides most of these functions, but here, we take two of them, i.e. profiling and viewshed analysis, as examples to illustrate the 3D analysis functionalities of GeoV&A. The results of 3D analysis are usually sent to the 2D and 3D visualization modules through URL encoding for display and interaction.

5.2.1. *Profile graph creation*

The profile graph tool uses a line file (e.g. 'road.shp') and a DTM TIN file (e.g. 'dtmtin2') entered by the user in the Webpage to create a graph that shows the height measured along the line. Figure 10 shows the result of the 'Create profile graph' function. This graph is used to evaluate the difficulty of building a mountain road. The creation of a profile graph is a relatively simple task, and is thus realized by Java programs on the client side.

5.2.2. *Viewshed analysis*

Determining what is visible on a surface from a set of one or more locations is useful for a wide range of applications, from estimating real estate value to locating communicating towers or placing military troops. The viewshed analysis function identifies whether the observation points that are specified on the input observation theme can be seen from each cell in a surface or cell locations can be seen from each observation point (Fisher 1996).

In GeoV&A, after users input two themes: an observation points file and a grid or TIN surface file, they can proceed to either browse the input maps or create the viewshed. The result of viewshed analysis can be shown as both 2D map (figure 11) and 3D VRML formats (figure 12). From 2D visualization, it is found that the observation post cannot be seen by most of the right part in the map, but it is difficult to understand the reasons. Through the 3D VRML model and the interaction like 'zoom in' and 'tilt', we can, however, easily find that there is a steep slope on the right of the point, which hides it from the right part of the map.

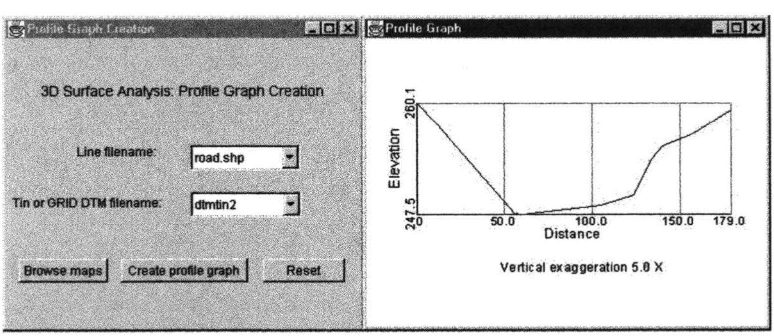

Figure 10. Result of a profile graph.

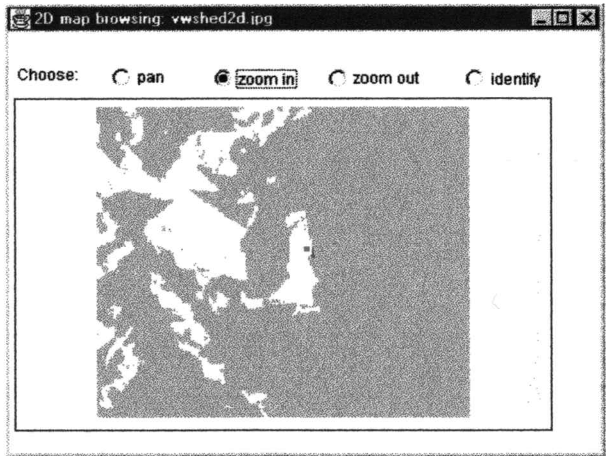

Figure 11. 2D map display of the viewshed analysis result.

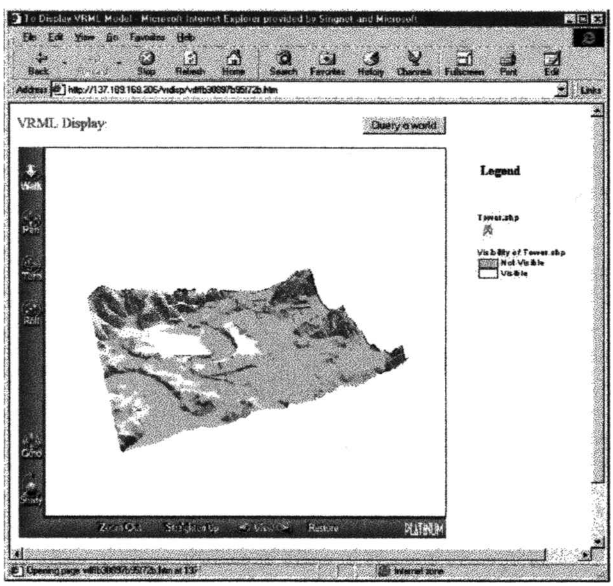

Figure 12. 3D VRML display of the viewshed analysis result.

5.3. *VRML interaction*

The 3D visualization and analysis functions described above generate VRML models. The user's interaction with these models, such as querying, manipulation, analysis and animation of the worlds, replicates and improves on the way a user interacts with the real world. It is, therefore, of importance to incorporate this functionality into the toolkit.

The interaction with VRML worlds can now be realized by interfacing Java or JavaScript with VRML 2.0 (Brutzman 1998). Currently, two methods are used for the interaction, namely using the Script node in VRML and the External Authoring Interface (EAI) in Java (Brown 1999). By using the Script node, the VRML scene can invoke a Java script linked with the node internally to operate on the scene.

Alternatively, EAI allows users to control the VRML scene contents externally using a Java applet on a Webpage. In GeoV&A, we use the EAI method for a flexible interaction with the VRML scene generated by the 3D visualization or analysis module. At present, the function of querying a world has been developed. After a user selects the 'query a world' button above the VRML scene (figure 13), an event was sent to the VRML browser to temporarily make the 3D scene reactive, which then allows a touch-sensor to return the coordinates pointed to by the mouse. After coordinate transformation in the Java program, the worlds are searched on the basis of the 2D map, from which the VRML model is generated. Finally, the attributes of the selected world are displayed in a pop up window. The above VRML interaction functions are performed by a Java applet on the client side.

6. Discussions and conclusions

A full integration of GIS, VR and the Internet can dramatically increase GIS capacity in spatial data visualization and analysis, and extend its decision support role in applications. This paper has demonstrated a hybrid approach to developing an integrated visualization and analysis environment on the Web by merging client- and server-side applications. Table 2 summarizes the allocation of different functions in GeoV&A to both the client and server sides. Suppose these functions could also be performed by the client-side and server-side approaches, the distribution of tasks are most probably like that given in table 2. These two approaches go to somewhat two extremes, resulting in a very thick client and a very thick server, respectively. Within a client-side approach (Kahkonen *et al.* 1999), creating an applet capable of doing a comparable task to GeoV&A is likely to be of a similar size, about 8 Mb. It is clearly not appropriate to be constantly sending applets this large across the network. Similarly, with a server-side approach (Huang and Lin 1999), two issues

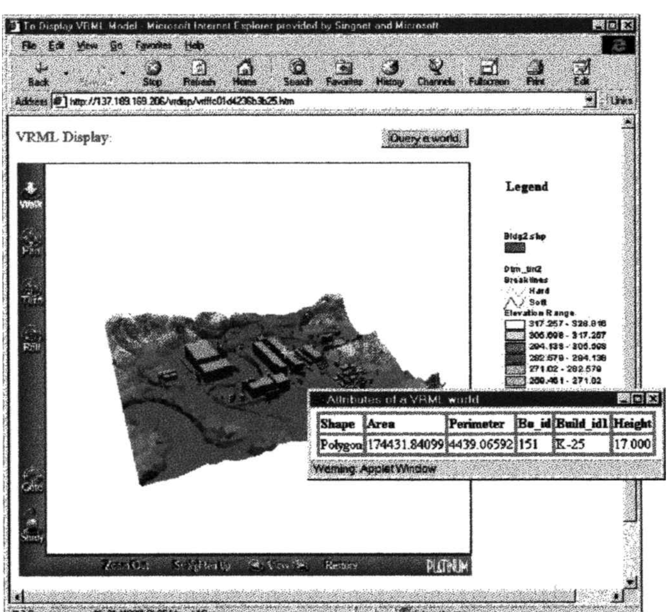

Figure 13. Querying worlds in a VRML model.

Table 2. Allocation of different tasks in GeoV&A using the hybrid approach in contrast to client-side and server-side approaches.

Approaches / Function	Hybrid appr. client-side	Hybrid appr. server-side	Client-side appr. client-side	Client-side appr. server-side	Server-side appr. client-side	Server-side appr. server-side
Command selection and data entry	✓		✓		✓	
Parameter correctness checking	✓		✓			✓
2D map browsing (pan, zoom in/out and identify)	✓		✓			✓
3D scene generation & export to VRML or image		✓	✓			✓
Profile graph generation	✓		✓			✓
Viewshed analysis		✓	✓			✓
VRML interaction (select, query, etc.)	✓		✓			✓

related to user interface and performance will arise (see §3). It is sensible, therefore, to choose the hybrid approach.

The hybrid approach is a compromise solution, taking account of existing GIS and its 3D visualization and analysis functions, as well as the development of Internet computation methods. It offers in some sense the best of both worlds, in which the client and server sides share the responsibility. The server side provides the processing power for complex tasks such as 3D scene creation from original 2D maps or viewshed analysis results and export them to VRML models, while the client side is given the responsibility for the fine control of the system, as well as basic map operations (e.g. zooming, panning and identifying spatial features), simple surface analysis (e.g. profile graph creation) and VRML model interaction. The GeoV&A prototype system, based on this approach, provides a flexible and platform-independent interface through the use of Java, as well as a powerful application server supported by a commercial GIS. There is no doubt some other GIS analysis functions such as buffer, and overlay can also be added to the toolkit using the hybrid approach.

While the hybrid approach shares the advantages of both client- and server-side applications and the client-side has undertaken some tasks that are supposed to be done on the sever-side in previous solutions, it cannot overcome the hurdle of the CGI approach, primarily the performance issue, as a CGI application needs to start up a new process for each request even the one like parameter correctness checking. Fortunately, the introduction of Java servlets has offered promise in remedying this (Huang and Worboys, 2001). The feasibility of using Java servlets along with the ArcView GIS in our case is to be examined.

Similarly there are concerns over VRML due to the increasing attention on the Java 3D API (Sowizral et al. 1998). While VRML is itself evolving (its next generation will be Extensible 3D–X3D), Java 3D is worthy of exploration, as it can allow the creation of a virtual environment without the use of plug-ins at all.

Experience with the prototype system also suggests further research is required on the extension of the hybrid approach. At the current stage, different tasks have been arranged in the toolkit and are allocated to the side specified in advance. A challenge is to develop an intelligent dispatcher agent, which can figure out workloads of different tasks in terms of data size, user number, and even existing cached data, and then dynamically allocates them to an appropriate side or both sides. This could increase the effectiveness of automatic load balancing. 3D analysis functions can also be conducted on the VRML model directly to suit different requirements. New methods and algorithms for this may need to be studied accordingly. Finally, future work will be incorporating environmental models into the framework of the full integration of GIS, VR and the Internet for supporting collaborative decision making.

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