A 2D/3D Hybrid Geographical Information System

Stephen Brooks*
Faculty of Computer Science
Dalhousie University
Halifax, Nova Scotia, Canada

Jacqueline L. Whalley†
Department of Computer and Information Sciences
Software Engineering Research Laboratory
Auckland University of Technology, New Zealand

Abstract

We present a unique Geographical Information System (GIS) that seamlessly integrates 2D and 3D views of the same spatial and aspatial data. Multiple layers of information are continuously transformed between the 2D and 3D modes under the control of the user, directly over a base-terrain.

Although 2D/3D hybrid (or combination) displays are now widely used in medical applications such as tomography, they have not been explored to any great extent in GIS applications. And although many existing commercial 3D GIS systems have 2D views they are typically isolated from the 3D view in that they are presented in a separate window. In this paper we introduce a 2D/3D hybrid GIS that allows the user to view the 2D data in direct relation to the 3D view within the same view.

CR Categories: I.3.8 [Computer Graphics]: Applications; I.3.6 [Computer Graphics]: Methodology and Techniques – Interaction Techniques.

Keywords: 2D and 3D visualisation, geographical information systems, combination display, navigation.

1 Introduction

In many interactive computer graphics applications, maps in three dimensions are central to enabling the exploration, presentation and manipulation of geographical data. 3D maps can be used by GIS specialists and as tools for presentation of spatial data to non–experts [MacEachren 1994]. Advanced graphical libraries such as openGL and VRML enable effective modelling by rendering the third geographical dimension [Shan 1998]. Here we present a 2D/3D hybrid GIS developed using OpenGL. This system provides users with the advantages of a 3D GIS while still retaining the familiar and useful 2D view of spatial data as required.

* sbrooks@cs.dal.ca
† jwhalley@aut.ac.nz

2 Background

Until recently most geographical information systems (GIS) have only had the capability to visualise information in two dimensions (2D GIS). Such systems are still used widely by geographic information professionals and much of the current research and development still lies in this traditional map-based approach. Although 2D GIS can be used to perform numerous spatial analyses and applications, visualisation is generally limited to viewing either individual GIS layers or the results of GIS analyses [Zlatanova 2004]. Because the world we live in is in three or more dimensions, focus has shifted towards the development of GIS in three dimensions. Though until recently a 3D GIS would exhibit delayed responses to a user requested database query or a geographic location to the time that the result was displayed [Faust 1995].

3D GIS have now become a reality due to pipelined 3D graphics and efficient terrain visualisation algorithms and many GIS have become available on the web. Examples of on-line GIS systems include Terrafly [Rishe 2004], GeoVR [Huang 1999] and TerraVisionII a flyby global GIS [Reddy 1999]. Two particularly interesting applications are GeoZui3D [Ware 2001] and VGIS [Lindstrom et. al. 1997]. The first, GeoZui3D is a 3D marine GIS that supports real-time input and texture mapped imagery using a simple viewpoint control method that links multiple views. Secondly, VGIS is an integrated global GIS and visual simulation system that supports multi-resolution terrain elevation and dynamic 3D objects. 3D GIS may be employed in many facets of everyday life such as urban planning, environmental decision making, flood, forestry, agriculture and military operations to name but a few application domains. All these application domains require different skills and motivators on the part of the GIS user. Nonetheless it is important that a common framework be applied such that the same data may be accessed for different purposes [Clematis and De Martino 1998].

Several GIS systems have the capability of creating three-dimensional perspective images using elevation data for geographic areas with GIS variables (such as population distribution or land use) overlaid. Typically this is simply used for illustration, and there is limited scope for the analysis of this perspective imagery. Additional information must be provided along with the perspective image in order to make measurements of size and shape. The perspective images are generally accepted as showing the relationships of the GIS data to the natural terrain, but have limited the efficacy of the perspective images to 'show and tell' type applications [Faust 1995]. Moreover, this representation only permits the user to view map layers as a single entity rather than being able to visualise the layers as a combined overlay representation and as

individual entities in the same way that is possible with 2D GIS. Faust argues that a true 3D GIS must enable the following functions: a realistic representation of the third dimension in the data and in visualization, free movement of the user within the three dimensional representation, normal GIS functions, such as query and overlay (but within 3D data space) and visibility functions such as line of sight estimation.

Gaining insight from 3D spatial datasets is particularly challenging largely because the high data density makes it difficult to view all the data at once and it is difficult to display multivariate data in a meaningful way. Moreover, there is difficulty viewing information in 3D GIS when the terrain is hilly due to elevated regions in the terrain occluding data. To overcome this 3D GIS may display the terrain from several different viewpoints.

Studies have shown that 2D views are often used to establish precise relationships, while 3D views help in the acquisition of qualitative understanding [Springmeyer 1992]. Both dimensionalities of view therefore have distinct advantages. This has led us to propose a unique 2D/3D combination GIS that allows the user to enjoy the benefits of dual visualisation modes. The rationale for our novel GIS is further supported by Troy et al. [2004] who found that combination 2D/3D displays are useful for precise orientation and positioning tasks. Moreover when compared with 2D displays they found that combination displays offer performance as good or better. 2D/3D combination displays (such as Orientation Icon and ExoVis) now exist for applications other than GIS. However, little has been done to optimise such a combination in GIS.

One of the main limitations of hybrid or combination systems that do exist is that they display the 2D and 3D views alone. Döllner and Hinrichs [2003] have developed a technique for displaying dual texture layer maps in 3D in order to facilitate information gathering from a thematic 3D map with all the layers presented in a single Y directional mesh. They use a weighted texture interpolation to display regions of limited interest. The α-texture is pre-computed or specified interactively at a low resolution. The second texture provides a highlighted region of a thematic map using a "thematic lens". Although this method does enhance the required region it does not overcome the elevated terrain feature occlusion problem except by providing the user with a new bird's eye view that removes any third dimension information being conveyed to the user.

3   Overview

Our system consists of two main visual data elements, the first being the 3D base-terrain. This base-terrain is comprised of the topographic data that is initially read into the GIS. The second is the vertical layering system. As the user interacts with the system one or more elevated layers may be loaded. These elevated layers are the components that make this GIS a hybrid or combination system. The layers may be elevated to be a true 2D visualisation of the base-terrain. The base-terrain itself must be made composed of at least one spatial layer (topography) and may have one or more aspatial layers (visualization data) integrated into it. In order to build the base-terrain and the elevated layers we have taken advantage the efficient clipping and texture facilities supported by OpenGL. A detailed discussion of the features integrated into our hybrid system follows.
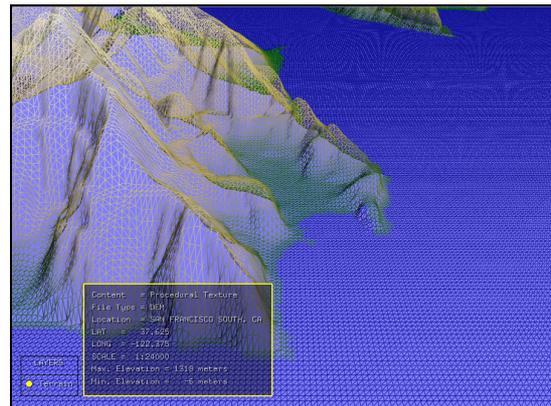
Figure 1: A regular grid DEM shown in wire-frame mode.

4   The 3D Elevation Base Terrain

The 3D base-terrain is built from Digital Elevation Model (DEM) data. DEM data is a regular grid of terrain elevation values that is placed on a grid specified by the geographical location of the elevation value. Each elevation point in the DEM is interpolated from a spot height measurement or contour data [Yu et. al. 2004].

In 3D GIS two approaches are available for constructing a 3D model from DEM data. The first approach is to use TIN (Triangulated Irregular Network) as a global surface model [Hoppe 1996; Hoppe 1997; Lounsbery et. al. 1997] and the second is to employ direct processing of all points as a regular grid [Lindstrom et. al. 1996]. For the first phase of development we have chosen to use the direct processing approach. Figure 1 shows a regular grid DEM in wire-frame.

4.1   Texturing, Shading and Lighting

In order to produce an accurate final appearance, we have the option of integrating high resolution satellite images as textures on our wire-frame mesh. However, care must be taken when registering satellite imagery onto DEM data. In addition, it may be necessary to mosaic multiple satellite images due to imperfections on individual images, particularly for cloudy regions.

In the absence of (or in addition to) good satellite images, a procedural texture can be generated based on elevation values. Our system generates a standard texture with colours ranging from blue, below zero elevation, up through brown, green and white. In addition, there is a modest degree of fractal noise that is added to the texture in order to avoid an overly sterile appearance.

Troy [2004] found that shadows play an important role in conveying information to the user of 3D information systems. They reported that displays with shadows had lower difficulty ratings than 3D rotated [St. John 2001] or 2D displays largely due to that fact that 3D rotated displays made it difficult to estimate height. They concluded that displays with shadows can result in effective 3D displays but only if the light is placed in a

very specific position in relation to the object of interest. In our GIS, the user has a choice with regard to light positioning and orientation. The light position can either be fixed relative to the camera position or fixed relative to the base-terrain. Also, the light can either be a spotlight or directional.

5   Layer Combination Visualisation

What gives our GIS its unique character are the multiple layers of information that can be continuously raised or lowered by the user directly over the base-terrain (see Figure 2). A typical layer is a square texture-mapped grid of height values that are translated vertically. The layer's texture can either be a satellite image, a procedurally generated texture based on elevation data, or a DLG (ArcView™ Digital Line Graph) vector data layer pre-computed onto the texture mapped geometry. When translated skywards, the height values are gradually flattened into a completely flat 2D texture mapped grid shown with perspective projection. Each layer's translation is set with an associated user-positioned control ball. The colour of the control ball is unique for each layer. In addition the layer is trimmed along its edge with the same colour as its associated control ball.

The layer's geometry is the same as the terrain itself. But, in addition to being (possibly) flattened, the layer is clipped on 4 sides with 4 clipping planes that are perpendicular to the layer. Each clipping plane is the same distance from the centre of the layer but along four opposing vectors. This ensures that we see a layer as a square area of the grid rather than the entire terrain (see Figure 3). Since the only difference between a layer and the base terrain is that the layer is a clipped and (possibly) flattened copy of the terrain, and is (possibly) texture mapped with a different image than the terrain, it allows us to use the same pre-compiled geometry lists for all layers as well as the base terrain.
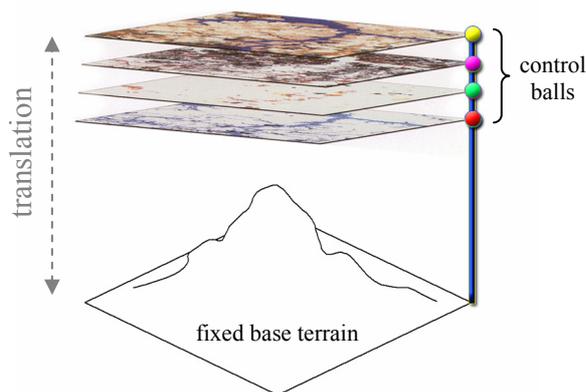
Figure 2: Multiple 2D thematic layers in a combinational display with a 3D base terrain. Vertical translation of layers is set with the associated control balls.
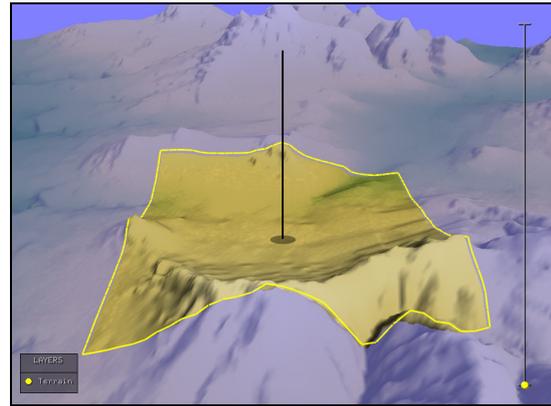
Figure 3: Layer shown as a terrain geometry clipped with 4 perpendicular clipping planes equidistant from the centre (shown as black vertical line). The original terrain is shown faded to highlight the relationship.

A layer is situated in its original latitude/longitude position relative to the base terrain, but raised vertically above the 3D elevation base layer. A layer is dynamically translated in the vertical direction by moving the layers associated control ball up and down at any point along the vertical slider control. The layer's orange control ball is shown on the vertical slider control to the right in Figure 3. When raising a layer from the 3D base terrain the layer starts with the corresponding terrain elevations, then gradually morphs into a flat plane as shown in Figure 4.

We note in this example how in Figure 4a the user is able to obtain a sense of the true 3D geometry of the terrain but only at the expense of not seeing information in valleys. In a standard GIS the user would be forced to accept this compromise. However, in our GIS the user is able to see the 3D grid as well as see all information within the layer by raising the layer to its flattened state (as seen in Figure 4c). When a layer is high above the terrain, it flattens out to a true 2D map. This allows the user to analyse information in 2D and also provides a way of viewing information that may have been hidden by near elevations in the 3D view. It also allows to user to move information out of view when he or she is not interested in the content of a particular layer. This is achieved by simply raising the layer to the top of the screen.

As the 2D layer is lowered it starts to extrude the elevations, morphing from a flattened state at a certain height, m, into its true 3D form at a height of zero. When translated down to its base position, the 2D Data Layer is linearly interpolated into the shape of the base terrain with individual data elements located at their corresponding terrain elevations.
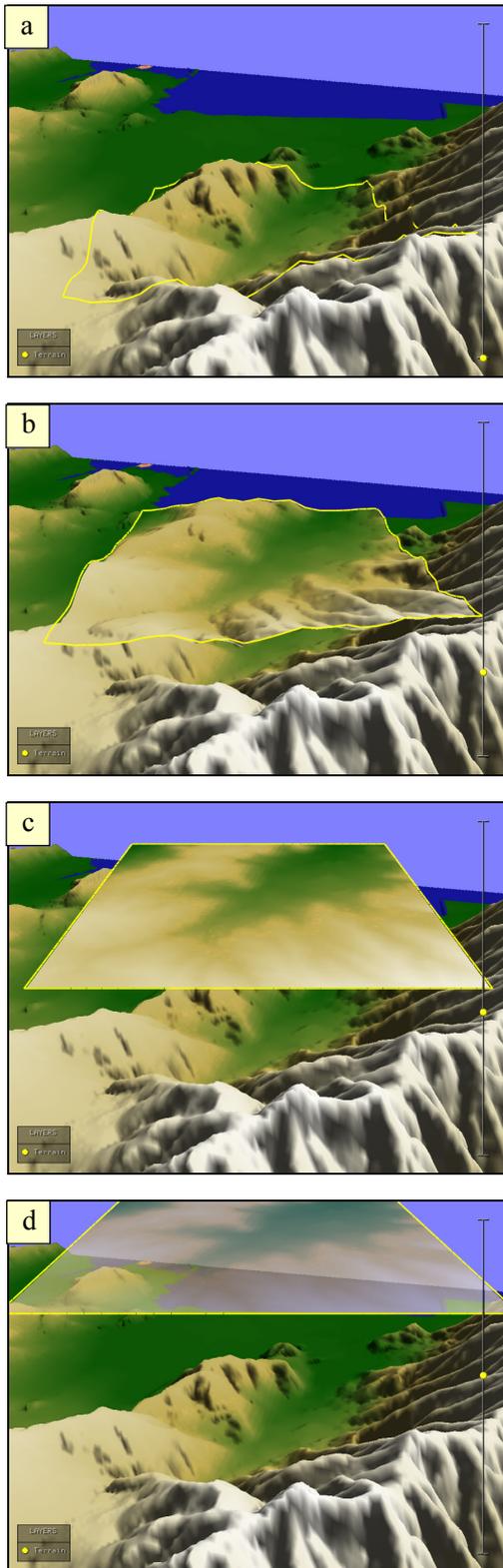
At a height of m the layer becomes flat, above this height the layer become increasingly transparent, until all that is visible is its coloured outline which trims the layer's edge. The trim is not affected by the change in transparency. An example of this is shown in Figure 4d. This allows the user the raise layers that are not currently in use cleanly out of the way. The persistence of the coloured trim is sufficient to remind the user of the layer's existence without blocking the background terrain or introducing unnecessary and potentially distracting visual data.

Finally, as the layer is raised, a ground level shadow (a dark outline of where the layer's edge maps to the terrain level) is always shown at the ground level. We propose that this ground level shadow will help users to mentally map the correlation between the data in the 2D/3D layers and the 3D base terrain (see Figure 5).
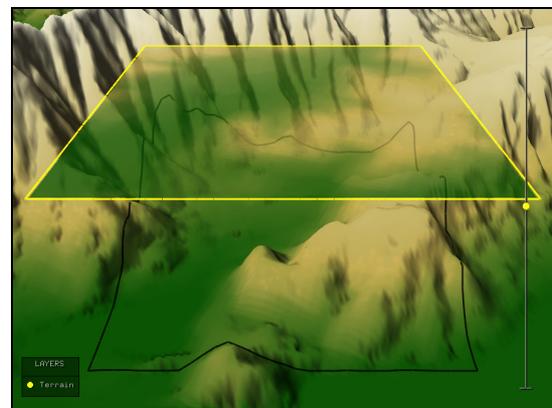
Figure 5: Ground level shadows as a projective aid.

5.1 Layer Content

Pseudo colour representations of data variables are often used to identify different regions within a raster GIS whereas line styles, widths, colour and symbolisation are used for data representation for vector GIS. True colour combinations of multiple raster GIS layers can also be accomplished for viewing the spatial relationships between the layers.

Our system facilitates multiple layers where the difference between the layers is the geospatial content. As stated earlier, a layer's texture can either be a satellite image, a procedurally generated texture based on elevation data, or a DLG (ArcView™ Digital Line Graph) vector data layer pre-computed onto the texture mapped geometry.

Figure 4: The layer is shown gradually rising from image a to image d. As the layer rises it morphs into a flat plane. Image c shows the layer completely flat at level m. Above level m, the layer becomes increasingly transparent as shown in image d.
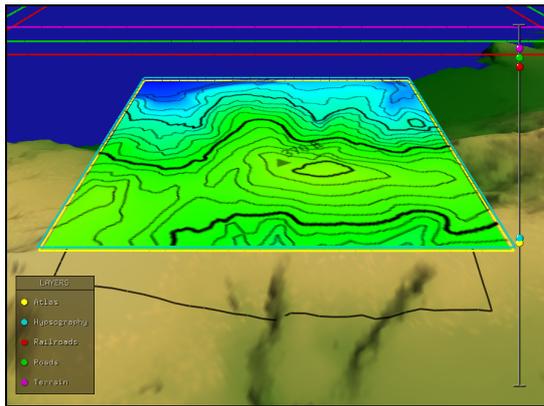
Figure 6: Five layers over a DEM terrain. Two layers have been raised to the flattening level with the black-line hypsography layer slightly above the atlas-coloured texture layer. The remaining three levels have been raise to the top of the screen. These layers have become completely transparent except for their colour trims.

The example in Figure 6 shows a layer set composed of the following layers:

- Atlas – procedurally generated texture layer where gradient colours are directly mapped to height values. The reader is directed to the following section for more information regarding the gradient mapping.

- Hypsography – Transparent DLG layer with black-line contour data.

- Railroads – Transparent DLG layer with black rail-track data.

- Roads – Transparent DLG layer with black-line road data.

- Terrain – procedurally generated texture layer that has the same colour content as the base terrain. Though seemingly redundant, this layer is useful when placed below transparent DLG layers. This allows the user to visualize transparent DLG layers as a flat 2D map over the original terrain coloration.

In the figure, the five layers are shown over a San Francisco DEM terrain. Two of the layers have been raised to the flattening level. The transparent black-line hypsography layer is placed slightly above the atlas-coloured texture layer. The remaining 3 levels (terrain, railroads, and roads) have been raised out of the way to the top of the screen. These layers have become completely transparent at this level except for their purple, red and green edge trims, respectively.

5.2 Layer Legend

With multiple layers present, it is necessary to provide a legend that indicates the content type of each layer. The main legend is shown in Figure 7 in which each layer is given a single word description next to a ball of the same colour as the layer's control ball and edge trim.

However, because there are multiple types of data in the various layers, it is not feasible to place all the information in a single legend. This would require too much screen space and may also be too much visual information to digest. In fact what we require are multiple legends, one for each layer.

Our solution to this issue is to generate separate pop-up legends for each layer when the user clicks on the appropriate entry in the main legend. Meta-data about each layer listed in the main legend in the viewing window is available by selecting the layer name or colour ball in the layer legend (Figure 8). This layer specific meta-data is shown in a semi-transparent pop-up legend to the right of the main legend.

Figure 7: Legend showing five layers.
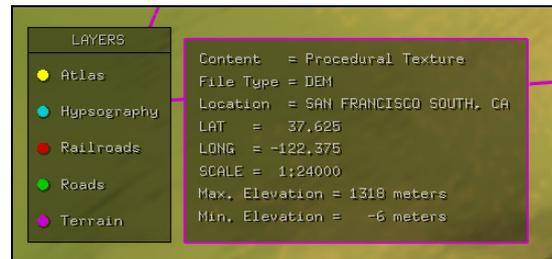
Figure 8: Text based meta-data pop-up legend for Terrain layer.
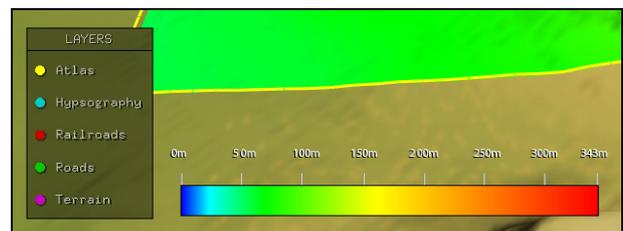
Figure 9: Image based meta-data pop-up legend for Hypsography layer.

The meta-data shown depends on the type of layer. For instance, in the case of the terrain layer, the meta-data includes the following textual information regarding the DEM terrain data-file:

- Content type of the layer
- Terrain file type
- Location description
- Terrain base latitude/Longitude
- Scale
- Minimum/Maximum elevation

Figure 8 shows an example of a textual meta-data legend.

Each auxiliary meta-data pop-up legend is trimmed with the same colour as the control ball for the layer and the trim on the layer itself. The consistent use of the layer's assigned colour provides a visual cue and structure to the relationship between the layer controls, layer data and layer meta-data. This application of consistent colour coding finds support in user interface design principles [Hix and Hartson 1993]

However, textual information is not appropriate for all layers. For the Hypsography layer which maps height values to a colour gradient, it is more appropriate to display the colour gradient to elevation mapping as an image. This alternative meta-data is shown in Figure 9.

5.3 Camera Control and the Layer System

We now describe how the virtual camera relates to the layer system. The layer system's position is fixed relative to the virtual camera meaning that the entire layering system moves with the viewer as they move across the landscape. The 2D layers are scaled and rotated synchronously with the 3D base layer view.

Translational movement of the camera over the base terrain is controlled with the arrow keys. When navigating through the terrain, the camera height is automatically adjusted based on terrain height under and in front of the camera. The height is placed a certain distance d above the average local height of the terrain. The averaging of terrain elevation is done in a circular area around the camera position. The averaging results in the smoothing of the camera height adjustment, mitigating the effect of local bumps in the terrain and enables the user to avoid having to constantly adjust the camera height in order to remain above the terrain.

The user can control the rotation of the camera around the centre of the layer system by using the mouse. By holding down the middle mouse button and moving the mouse to the right or left the camera is turned in the direction of the mouse. The rotation is pivoted around the centre of the layer system. This ensures that the user is viewing a consistent terrain location when rotating (Figure 10).

6 Additional Navigational Tools

Past research has shown that it is easy to get "lost" or disorientated in a 3D GIS. A number of navigational methods have been proposed to help orientation and comprehension in a virtual environment [Darken 1993]. Previous work has proposed navigational metaphors such a human walker [van der Linden 2004]. Accordingly, we have integrated a number of navigational aids into our GIS system.
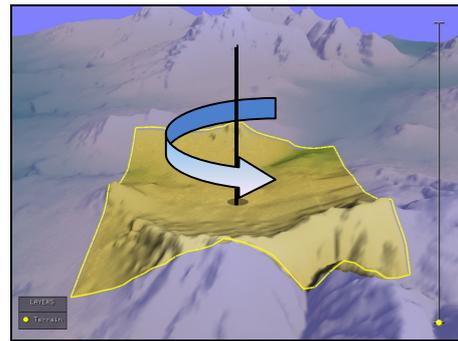
Figure 10: Rotating the camera around the layer centre.
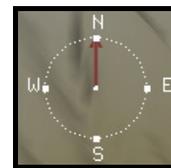
Figure 11: Semi-transparent directional compass.
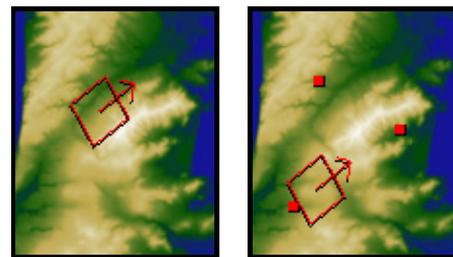
Figure 12: Mini-map with indicator box and arrow (left).
A series of jump sites (right).

A standard directional compass is always present, pointing north (see Figure 11). The compass background is rendered to be semi-transparent in order for it to be as unobtrusive in the interface as possible. A compass was noted as an essential tool for orientation by Köller et. al. [1995].

We have also provided the user with a mini-map (or locator map) as a further orientation tool. The mini-map gives an overview of the entire terrain and the current camera location is indicated by a shadowed red box. This box represents the area of the terrain that the user is currently viewing. An arrow indicates the direction in which the camera is pointed along the terrain (see Figure 12, left).
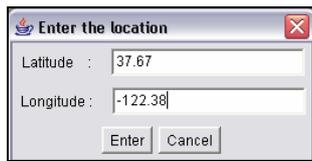
Figure 13: Jumping to a location with precision.
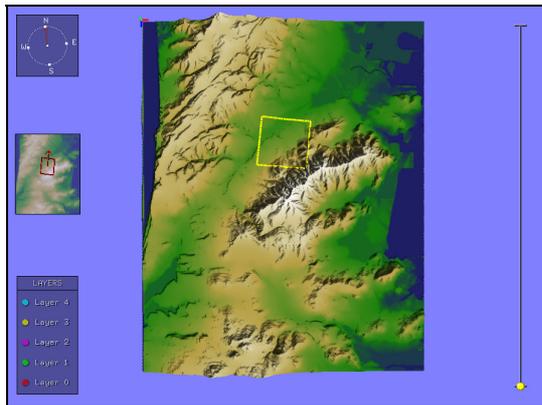
Figure 14: Top-down view of the terrain.

Figure 15: Using fog as a distance cue.

When Köller [1995] tested a system designed for the military, the soldiers found traditional fly-by navigation difficult to use and requested the ability to jump to a location directly by inputting map co-ordinates. We have implemented the ability to jump from location to location in our hybrid system in two distinct ways. The first way is via mini-map interactions and the second way is by entering a latitude/longitude position, in decimal degrees into a dialog box. The former is a fast and integrated solution in that the user is not forced to switch context into a numeric modal dialog, while the latter provides a more precise way of jumping to a new location.

The mini-map allows the user to "jump" between locations on the terrain by directly selecting a location on the mini-map. This positions the camera at that location and also stores that location in a list for later use. The current camera location can also be stored in the list by pressing the 's' key. The user can therefore either set the position within the mini-map directly with a mouse click, or move freely over the terrain and store the current camera position with a key press. Each stored location is drawn as a shadowed red dot in the mini-map (see Figure 12, right). Once one or more locations have been stored the user may successively jump to the locations. The user cycles through these jump points by pressing the 'j' key. Once these jump locations are no longer required all mini-map positions may be cleared with the 'c' key.

Alternatively, a precise geographical location within the terrain may be jumped to by specifying a decimal degree location as latitude and longitude in a separate modal dialog (see Figure 13).

Two further facilities that our GIS offers for spatial navigation and distance perception are a top-down view and fog rendering. For a detailed spatial overview, the user can switch to a top down view of the entire terrain at any time (Figure 14). Enabling fog provides an additional distance cue, and can minimize possible distractions by objects in the distance. We add a further nuance in that the fog does not affect the layers. By restricting fog to the base terrain we achieve a similar result, in terms of visualisation, to the texture-based approach adopted by Döllner and Hinrichs [2003]. As a cautionary note, the benefits of employing the fog functionality must traded off against the loss of orientation with regards to where the camera is in relation to the rest of the terrain.

7 Conclusion and Future Directions

We have developed a unique 2D/3D hybrid GIS with multiple navigational tools. The key components of the GIS are:

- Layers
  - Layers flatten at a certain level, m, then become transparent above that level.
  - Layers can contain solid texture or transparent vector data.
  - Each layer is trimmed along its edge with the same colour as the layer's control ball and legend ball to assist identification when multiple layers are raised.
  - Each layer is drawn as a pre-computed display list, cropped with 4 vertical clipping planes. Each clipping plane is rotated and translated with the camera so that it is always synchronized.
- Control slider
  - The vertical control slider contains a single control ball for every layer
  - Each control ball is given a unique colour to identify individual layers within the legend.
- Legend
  - Each layer is listed in the legend along with a colour coded ball, mimicking its associated control ball.
  - Meta-data for each layer is presented in auxiliary pop-up legends.

- Navigation
  - The layer system's location and orientation is tied to the camera.
  - The camera's height is automatically computed from the local average height surrounding the camera.
  - Additional navigational tools include: a compass, mini-map, numeric locator, top view and fog.

However, as is the case with new research directions, there remain many opportunities to be explored and choices to be made as to how this GIS will be taken forward.

In the next phase we propose to undertake a usability study to confirm that a hybrid system such as ours is advantageous to the GIS community.

One of our key objectives in developing this system is to provide GIS users with the advanced query facilities that they are accustomed to using (in traditional 2D GIS) for decision making and spatial/aspatial data analysis. Integration of such querying capabilities will make our system a useful tool for decision makers, environmental scientists and many more potential users. The visualisation of query results as new layers should be flexible and integrate concepts such as 3D icons and labels. We need to consider how we will integrate spatial data that uses other models for the presentation of the 3D spatial data.

Furthermore, in order to provide fully-fledged data query functions we need to remove ourselves from the text file based paradigm of 3D graphics and look at ways of integrating 3D spatial data into a database management system (DBMS) that will allow us to fuse spatial and aspatial data thus enabling interactive querying. Many researchers such as Li [2001] are starting to address this issue and although a definitive solution is not yet available, steps forward are being made in this area of research.

De Kemp [2000] identified two key needs in 3D GIS. The first is the ability to display all relevant 2D map-based data. This includes symbolised structure data, geographic reference features geological contacts and map units co-registered imagery (such as orthophotos, satellite or airborne geophysical data). Secondly, an intuitive 3D interpretive editing environment is needed which allows sufficient dynamic rotations, translations, scale jumps and data selections. While our system addresses the second requirement we still need to devise a strategy to fulfil some of the features in the first requirement.

Although we have many navigational aids in our system the GIS user community still retains the traditional GIS paradigms for navigation. One such paradigm is the requirement to change scale frequently. GIS Users need to be able to zoom in and out as they can in 2D GIS systems. This does present a problem in 3D GIS that take advantage of the 'flyby' paradigm. We propose to develop this "zooming' capability using a modulating velocity approach based on depth sampling as recommended by Ware and Fleet [1997].

A further interesting extension to the system would be the integration man-made 3D objects for data with high resolution and small geographical area.

In summary, we have developed a novel 3D GIS, one in which there is the potential for many future enhancements.

References

CLEMATIS, A. AND DE MARTINO, M. 1998, Using GIS to Visualise Environmental Information A Case Study Based on the Digital Terrain Models. *Computer Graphics International*, 123-127.

DARKEN, R. P. AND SILBERT, J. L. 1993. A Toolset for Navigation in Virtual Environments. In *Proceedings of the ACM Symposium of User Interface Software and Technology*, 157-165.

DÖLLNER, J. AND HINRICHS, K. 2000. Dynamic Maps and Their Texture-Based Design. *Computer Graphics International,* 19-24, 325 - 334.

EBERT, D., MUSGRAVE, K., PEACHEY, P., PERLIN, K., AND WORLEY, S., 1994. *Texturing and Modeling: A Procedural Approach.* AP Professional.

FAUST, N. 1995. Raster Based GIS. *GIS Development in North America*, GIS World Inc., July.

HIX, D. & HARTSON, H.R. 1993. *Developing User Interfaces: Ensuring usability through product and process*, Wiley, New York.

HOPPE, H. 1996. Progressive Meshes. In *Proceedings of ACM SIGGRAPH Computer Graphics*, 99-108.

HOPPE, H. 1997. View-dependent refinement of progressive meshes. In *Proceedinsg of ACM SIGGRAPH Computer Graphics*, 189-198.

HUANG, B. AND LIN, H. 1999. GeoVR: a web-based tool for virtual reality presentation from 2D data. *Computers and Geosciences*, 25, 1167-1175.

KOLLER, D., LINDSTROM, P., RIBARSKY, W., HODGES, L. F., FAUST, N. AND TURNER, G. 1995. Virtual GIS: A Real-Time 3D Geographic Information System. In *Proceedings of the IEEE Conference on Visualization '95,* 94 - 100.

LI, J., JING, N. AND SUN, M. 2001. Spatial Database Techniques Oriented to Visualization in 3D GIS. In *Proceedings of the 2nd International Symposium on Digital Earth*.

LOUNSBERY, M., DEROSE, T., AND WARREN, J. 1997. Multiresolution Analysis for Surfaces of Arbitrary Topological Type. *ACM Transactions on Graphics*, 16(1), 43-73.

LINDSTROM, P., KÖLLER, D., RIBARSKY, W., HODGES, L. F., FAUST, N. AND TURNER, G. 1996. Real-Time Continuous Level

of Details Rendering of Height Fields. In *Proceedings of ACM SIGGRAPH Computer Graphics*, 109-118.

LINDSTROM, P., KÖLLER, D., RIBARSKY, W., HODGES, L. F., OP DEN BOSCH, A., AND FAUST, N. 1997. An Integrated Global GIS and Visual Simulation System. Technical Report GIT-GVU-97-07, Georgia Institute of Technology.

MACEACHREN, A. M. 1994. Visualization in Modern Cartography. ed. A. M. MacEachren and D. R. F. Taylor, Oxford, UK, Pergamon.

MORI, M. 2003, Integration of High Resolution (10m) DEM with Geographic Information Systems. In *Proceedings of the XXth ISPRS Congress Istanbul*, vol. XXXV, part B2, 392-396.

ORLAND, B. 1994. SmartForest: A 3-D interactive forest visualization environment. In *Proceedings, Decision Support 2001 Resource Technology '94,* American Society for Photogrammetry and Remote Sensing, Washington, DC., 181-190.

REDDY, M., LECLERC, Y., IVERSON, L. AND BLETTER, N. 1999, TerraVisionII: Visualizing Massive Terrain Databases in VRML. *IEEE Computer Graphics and Applications,* 19(2), 30-38.

RISHE, N., SUN, Y., CHEKMASOV, M., ANDRIY, S AND GRAHAM S. System Architecture for 3D Terrafly Online GIS. 2004. In *Proceedings of the IEEE Sixth International Symposium on Multimedia Software Engineering (MSE2004)*, 273-276.

SHAN, J. Visualizing 3-D Geographical Data with VRML. 1998. *Computer Graphics International*, 108-110.

SPRINGMEYER, R. R., BLATTNER, M. M. AND MAX, N. L. 1992. A Characterization of the Scientific Data Analysis Process. In *Proceedings IEEE Visualization*, 235 – 242.

ST. JOHN, M., COWEN, M. B., SMALLMAN, H. S. AND OONK, H. M. 2001. The use of 2D and 3D displays for shape-understanding versus relative position tasks, *Human Factors*, 43, 79-98.

TROY, M., MÖLLER, T., ATKINS, M. S. AND KIRKPATRICK, A. E. 2004. Combining 2D and 3D Views for Orientation and Relative Position Tasks, In *Proceedings of the ACM Conference on Human Factors in Computing Systems (CHI 2004), CHI Letters*, 6(1).

VAN DER LINDEN, J., LI, J., LOBB, R., NOVINS K., AND WUENSCHE, B. 2004. Strider: A Simple and Effective Terrain Navigation Controller, *Proceedings of IVCNZ '04*, Akaroa, New Zealand, 21-23 November 2004, pp. 95-100.

WARE, C., PLUMLEE, M., ARSENAULT, R., MAYER, L.A. AND SMITH, S. 2001. GeoZui3D: Data Fusion for Interpreting Oceanographic Data. In *Proceedings of the MTS/IEEE Conference and Exhibition, Oceans 2001*, 3, 1960-1964.

YU, Q., CHEN, C., PAN, Z. AND LI, J. 2004. A GIS-based Forest Visual Simulation System. In *Proceedings of the Third International Conference on Image and Graphics (ICIG'04)*, 410-413.

ZLATANOVA, S., RAHMAN, A. R. AND SHI, W. 2004. Topological Models and frameworks for 3D spatial objects. *Computers and Geosciences*, 30, 419 – 428.