A review on 3D terrain visualization of GIS data: techniques and software

Che Mat RUZINOORA,B, Abdul Rashid Mohamed SHARIFFA, Biswajeet PRADHANA,C,* Mahmud RODZI AHMADC and Mohd Shafry Mohd RAHIMD

AGeospatial Information Science Research Centre (GISRC), Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia; BCollege of Arts and Sciences, Universiti Utara Malaysia, 06010 UUM Sintok, Kedah, Malaysia; CDepartment of Civil Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia; *Faculty of Computer Science & Information Systems, Universiti Teknologi Malaysia, 81310 UTM Skudai, Johor, Malaysia

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3D terrain visualization of geographic information systems (GIS) data has become an important issue in recent years. This is due to the emergence of new geo-browsers such as Google Earth, widely popular among users. The availability of 3D representation tools has increased the demand for 3D terrain visualization. The aim of this paper is to review the literature related to the 3D terrain visualization of GIS data from the first map produced until the online mapping era. The reviews are divided into four different sections: manual visualization of 3D terrain, automated visualization of 3D terrain, online visualization of 3D terrain, and software for visualizing 3D terrain. Then, the paper compares between the different types of systems developed by various authors based on the capabilities and the limitations of the system. Some of the techniques have their own strengths and limitations which solve the problem in 3D terrain visualization. However, the research on improving 3D terrain visualization is still ongoing. This is due to the popularity of online environments and mobile devices that render 3D terrain. This review paper will help interested users understand the current state of 3D terrain visualization of GIS data in a better way.

Keywords: terrain visualization; geographic information systems (GIS); 3D terrain visualization; online 3D terrain visualization; remote sensing; Malaysia

1. Introduction

Geographic information systems (GIS) applications are moving towards 3D, as it has the capacity to better represent the real world. Currently most of these applications can be run in online environments. The emerging of geo-browsers such as Google Earth, Microsoft Virtual Earth, and World Win, made the demands for these kinds of applications increase tremendously. 3D terrain visualization is a most important part of this technology. Therefore, the aim of this paper is to provide a comprehensive review of 3D terrain visualization for GIS data. The arrangement of this paper starts with the review of manual visualization of 3D terrain from the earliest work done (2D) up to the currently available techniques (3D). The second section continues with a review of automated 3D terrain visualization. This section is divided into three subsections: photorealistic approaches, nonphotorealistic approaches, and real time and nonreal time approaches. The third section reviews online 3D terrain visualization. The fourth section reviews the software for visualizing 3D terrain. Section 5 discusses the overall techniques for visualizing 3D terrain in term of timelines and concludes the paper. Figure 1 shows the overall process flow of the existing literature on 3D terrain visualization of GIS data.

2. Manual visualization of 3D terrain

Manual representation of terrain has been a challenge to map-makers since the earliest maps were produced. Some of the earliest maps of terrain show mountains as rounded “molehills”: the simple, uniform, side views of a regularly rounded dome (1) (see Figure 2(a)). The arrangement of these “molehill” symbols evolved over time to incorporate variations in size and shape as well as being shaded to give an impression of illumination. Dowson (2) has provided a good review on this kind of technique. He produced a table that categories the manual representation of terrain into six different classes. He described every class as having its own strengths and weaknesses. Table 1 lists the techniques and provides examples of each class with additional methods.

As shown in Table 1, spot heights are classified as surface specific features. Mulcahy (3) described spot heights as the height value measured upwards from a...
base datum on the earth’s surface and called depth values as soundings. Similarly, skeletal lines are also classified as surface specific features. It includes the ground plan of watersheds, drainage networks, and lines of all types which divide up the terrain (1). These skeletal lines are often used as a construction aid for other methods of terrain representation. Therefore, according to Mulcahy (3), skeletal line drawings consist of mountain crests, ridge lines, and streams combined with spot elevations, annotation, and other texts from expedition reports and travel books. Improved visual perception of hill and mountain shapes can be enhanced through the addition of stream lines. Figure 2(b) shows one example of a skeletal line image.

Profiles are described as cross-sectional outlines of the earth’s surface and classified as a slice in Table 1.

Table 1. Classes for manual representation of terrain (adapted from Dowson (2)).

| Surface specific features | Spot heights |
|--------------------------|--------------|
| Slices                   | Profiles     |
|                          | Inclined profiles (Figure 3) |
|                          | Contours     |
|                          | Layer shading |
| Shading                  | Stippled relief |
|                          | Hachures (Figure 4(a)) |
|                          | 3D shaded contour |
| Pictorial                | Hill shading (Figure 4(b)) |
|                          | Molehill (Figure 2(a)) |
|                          | Physiographic |
|                          | Oblique regional view |
|                          | Block diagram |
|                          | Sketches     |
| Photographics            | Photomaps    |
| True 3D                  | 3D models    |
|                          | Globes       |

Figure 1. Overall process flow of the reviewed papers.

Figure 2a. Mountains in the shape of molehill.

Figure 2b. Skeletal lines (Courtesy: Imhof (1)).
The drawing of an individual profile may be of great assistance in visualizing relief and in the description and explanation of the landforms (4). Figure 3 shows one example of the profile line image.

Hachures are classified as shading in Table 1. Dowson (2) described hachures as short lines, drawn down the direction of slope. The hachures are arranged so that their end points begin and the end, much like contour lines, but at regular vertical intervals. Flatter terrain is drawn with longer hachures and steeper slopes with shorter hachure. The angle of the slope determines the thickness of the hachures. Steep slopes have heavier hachures compared to gentle slopes which have finer hachures. This system allows for easy identification of the slope direction and the change from ground level to steep slope. Cartographers can produce hachures in an objective and consistent manner. The variation of hachures is introduced by altering the thickness, shape, density, or length of the markings (Brandes (4), p. 93, report in Dowson (2)). Figure 4(a) shows one example of the hachure image.

On the other hand, Mulcahy (3) described shading as the gradation from dark to light in a single color according to specific principals for the purpose of creating a 3D effect. In contrast to the metric accuracy of contour lines, hill shading is primarily used for its visual effects. Figure 4(a) and (b) show examples of the hachure and hill shading image.

A pictorial method of representation of terrain, physiographic diagrams is classified by Robinson et al. (5) as a type of schematic map. These maps combine a planimetric base with an oblique viewing angle of terrain features. The base of a mountain symbol is corrected planimetrically but its peak may be offset by the oblique viewing angle. The purpose of these maps depicts the relationship between the landforms and their geology and geomorphology (3).

Mulcahy (3) explained block diagrams as a pictorial method used primarily for the portrayal of geologic relationships. It shows a portion of the earth’s surface and crust from an oblique viewing angle. The block diagram approach originated from geological reports illustrated with cross sections. Pictorial sketching was added to the section to add realism and related the surface expression with subsurface geology.

3. Automated visualization of 3D terrain

Automated methods for 3D terrain visualization include mosaics (a pseudo-coloring of the grid cells), profiles, contouring, vertices, wire mesh, polygon model, and photorealism (2). The great advantage of computer visualization of terrain data is quick and effortless image production especially with 3D diagrams. These are of great value but can be time consuming and tedious to produce using conventional cartography. Thiemann (6) referred to visualization as the process of using the computer model of the terrain or scene to create a picture. The final output is assumed to be a bitmap of pixels. Visualization can be thought as the process of taking 3D information and making a 2D image from it.
In contrast, Brodlie et al. (7) presented the scientific visualization technique as a means to explore data and information to gain understanding and insight into the data itself. Some of these techniques can be used for online 3D terrain visualization projects realizing the display of data in 3D. Figure 5 shows the overlapping method where one field data-set is shown as a surface net and another field data-set is shown as a shaded contour map. Moreover, Szemberg et al. (8) found that computer representation of a terrain surface can be represented by some form of discretization, either by means of grid (usually regular) or of a triangular irregular net.

3.1. Photorealistic approaches

Photorealism is a new trend in terrain computer representation. It attempts to make artificial images of simulated 3D environments that represent or depict the world. Foley (9) stated that image-based techniques will be used to capture photographically the fine texture detail and possibly the geometry of objects in the scene. Image-based techniques can create spectacular images because they capture the details that are not known. But Visvalingam (10) found that the image-based approach has a problem since it does not detect boundaries as inserted by the model-based approach.

Szemberg et al. (8) produced methods for object and terrain visualization by means of the combination of two algorithms, one for terrain data and one for objects. The purpose was to generate, aerial images of terrain with objects, efficiently and rapidly. In this work, terrain surfaces are represented by regular grids described by 2D matrices, one determining the height at each point and the other determining the texture. This research compared results obtained with two approaches. The first approach used OpenGL graphical system for visualizing both terrain and objects. The second approach used an optimized algorithm for visualizing the terrain; the image and the depth information obtained are then transferred to OpenGL, to be integrated in the scene containing the objects. By comparing of both approaches, the authors found that the second approach was the best when the method’s impact on the performance of visualizing terrain with objects was not a requirement.

Hurni and Räber (11) created the Atlas of Switzerland 2.0 that combines photorealistic and nonphotorealistic approaches to visualize terrain data. However, this system could be improved for an online implementation. Brooks and Whalley (12) introduced a technique to render terrain using a multilayer hybrid approach. This technique renders the same data as an image in 2D and 3D. Within the same view, the user has a capability to view the 2D data in direct relation to the 3D view. The system allows the user to exclude data which are not relevant. Six layers can be produced by the system including: a landmark layer, chart layers, direct layer painting, a 3D point layer, layer grouping, and the onioning of a layer control ball. However, this system does not provide advanced query facilities. The system also has not passed the usability study yet as it has only been tested by the researcher and therefore not subject to user testing. Table 2 shows different techniques for photorealistic terrain visualization.

3.2. Nonphotorealistic approaches

In recent years, most researchers have turned their attention away from photorealistic and towards developing nonphotorealistic rendering (NPR) techniques in a variety of styles and simulated media such as watercolor (13), technical illustration (14), and graphite pencil (15). All of these techniques are used in terrain visualization. Visvalingam and Dowson (16) proposed the P-stroke technique for sketching and visualizing terrain. Their work uses Visvalingam’s algorithm applied to a digital elevation model (DEM) in rows and columns to derive associated two area values with each cell. Filter tolerances are then used to select a subset of cells, referred to

| Authors               | Rendering technique                             | Outputs                                                   |
|-----------------------|-------------------------------------------------|-----------------------------------------------------------|
| Szemberg et al. (8)    | Combining terrain data and objects              | 2D matrices of regular grids containing 3D texture and height at each point |
| Hurni and Räber (11)   | Combining photorealistic and nonphotorealistic | 3D texture image of terrain with fogging                   |
| Brooks and Whalley (12)| Multilayer hybrid approach                      | Six layers: landmark, chart, direct layer painting, 3D point, grouping, and control ball |
as core cells. The core cells indicate the position where the strokes should be drawn. These cells are connected and extended along profile sections to form profile strokes or P-Strokes, which vary in length and direction, which simulate the pen stroke of an artist.

Ruzinoor (17) used silhouette rendering algorithms for visualizing the terrain as an artistic sketch. Silhouette rendering algorithms are one of the NPR techniques described by researchers as the lines between front-facing and back-facing polygons. They can be used to sketch terrain in 3D. The wireframe method introduced by Raskar and Cohen (18) and implemented by Liu (19) has been used for visualizing the terrain in terms of silhouette edges. It is found to be sufficient enough for visualizing the terrain as an artistic sketch. The results show that the silhouette rendering algorithm could be used in 3D terrain visualization and yields a very promising terrain image. However, Lessage and Visvalingam (20) reported that results from the silhouette rendering technique can be different when visualizing terrain using the luminance map technique. Their results produced an image which looks like human drawn illustration.

Ruzinoor and Nordin (21) enhanced the silhouette technique for visualizing the terrain using different data approach. The data for the terrain is extracted from the topography maps. Contour data from a topography map are converted from raster to vector (vectorization) in order to create grid terrain DEM. Vectorization software was used for producing these data. The data was then converted into a format suitable for existing 3D silhouette software. The results produced were compatible with terrain images similar to human drawn illustrations and look like an artistic style (Figure 6).

The latest NPR techniques for visualizing terrain were introduced by Bratkova et al. (22). They used the perceptual and artistic analysis of two panorama maps for creating mountainous terrain. When generating a texture image of the surface in an artistic style, they use perceptual metrics with an aesthetic flair. Their results are very promising for the visualization of the mountainous terrain.

3.3. Real-time and nonreal-time approaches

3D terrain visualization can be divided into two types; real-time visualization and nonreal-time visualization. The discussion in this section will be based on both types of visualization. Many techniques have been introduced by researchers in order to achieve the real-time terrain visualization in 3D. For example, research on reducing the size of terrain data by using compression techniques was conducted by Pradhan et al. (23–26). They used a second generation wavelet with a lifting scheme algorithm to reduce the data-set size for efficient online transmission of terrain data.

In the techniques which are not real time, Kofler et al. (27) pointed out the importance of data structures for 3D terrain visualization providing algorithms for efficient access to the visible portion of data needed to render each frame. However, there are still unsolved problems in choosing the database system. They found that an object oriented database (OODB) is not necessarily good for GIS, since testing shows that OODBs are too slow to provide the necessary bandwidth. Döllner et al. (28) introduced a new rendering technique related to level of details (LOD) for terrain models. LOD can be defined as complex models containing many triangles for representing terrain data. The technique is used for processing multiple multiresolution textures of LOD terrain models. The application is an interactive and animated terrain content design.

Ulrich (29) demonstrated how terrain meshes could be divided into a tree of independent images. This technique, called the chunk LOD in which children of a node represent the parent node, but at a higher LOD. Figure 7 shows how LOD could be divided into chunks.

Hesse and Gavrilova (30) demonstrated a new approach based on an adaptive real-time rendering algorithm using the real-time optimally adapting meshes (ROAM) technique. They demonstrated that this technique increases the rendering speed, smoothness, and realism of terrain visualization. They also did a quantitative analysis of culling techniques combined with an error matrix and found that backface culling was a less dominant viewing frustum.

Brodersen (31) has demonstrated how a geometric mipmap terrain engine can be adapted to efficiently render large scale terrains. It allows textures larger than what the graphics hardware is capable of displaying.
using a single texture. Figure 8 shows two images of terrain visualization developed using his technique.

Smullen et al. (32) developed a stereo display system for visualizing terrain from DEM data. LOD techniques have been used for maintaining acceptable display but however this system is not in real time. It utilized cost effective open source software when compared to the commercial ArcView 3D analyst software. This is different from the approach proposed by Losasso and Hoppe (33) who created a technique they call geometry clipmap for rendering the smooth terrain. Their technique allows the users to display the natural representation of terrain data. It is developed from cache nested rectangular extent pyramids to create view-dependent visualizations. An advantage of this system is that the compressed terrain data reduces rendering time.

Pajarola and Gobbetti (34) have done extensive survey on how multiresolution techniques can reduce the size of terrain data for achieving the real time visualization.

4. Online visualization of 3D terrain

The latest techniques for 3D terrain visualization involve online and mobile systems. Most of these applications for 3D terrain visualization are open source web-based systems. In tandem with the emergence and popularity of mobile devices, most of the new 3D visualization innovations are focused on mobile applications.

Leaver (35) produced good results on online 3D terrain visualization by using virtual reality markup language (VRML) for the Monterey Bay National Marine Sanctuary seafloor. His interactive system is composed of hundreds of topographic tiles to form a mosaic of the bay. It used QuadLOD node technique as proposed by the GeoVRML Working Group for controlling the resolutions of grid data. This means that when a viewer zooms closer to the terrain, the resolution increases to provide a superior granularity.

Araya et al. (36) proposed a flexible and efficient VRML-based terrain model placing side by side terrain models (tiles) of fixed size in 3D space. As the simplification of the display range changes, an automatic changeover mechanism for the LOD of the model becomes possible. Each tile is modeled by combining multiple grid models and useless polygons in the sea and lakes are curtailed. The automatic changeover mechanism for the model detail level regenerates the shape of the features of the terrain objects such as square and flat.

Zhu et al. (37) proposed and implemented a tile-based selective visualization method to facilitate 3D web surfing. They used the tile concept for development and built a geo-information query system based on 3D terrain visualization. The result is a web GIS prototype implementation featuring a hybrid 2D–3D interface.

Guth et al. (38) introduced the latest technique for rendering terrain data in a mobile device. Their technique involved three devices which are GIS, geographical positioning systems (GPS), and Pocket PC. These three devices are individually powerful but combining them together creates great efficiency. The system runs on a pocket PC acting as a client-server. It contains all data and performs all display manipulation. In order to visualize the terrain, the pocket PC transmits its position to the server and then http protocol is used for communicating between the client and server. The pocket PC then can automatically display high-resolution maps around its position with a single click on the stylus from the TerraServer. The main problem with this system is that the network handheld devices can only access limited imagery from the server.

In contrast, Zhang et al. (39) introduced a distributed virtual geographic environment system based on web services technology. This system provides users with a collaborative capability to interact with each other when making decisions on terrain visualization in terms of publishing multidimensional geo-data, simulating, and analyzing complex geo-phenomena.

Shiau et al. (40) proposed a new system for creating the 3D environments by combining the digital terrain model and Système Pour l’Observation de la Terre (SPOT) images of GIS with weather simulation of the particle system in networking environments. In order to make the system run in real time, several acceleration schemes are used including ROAM, view frustum culling, and LOD. A dead reckoning technique reduces the flow rate of the network to make the distributed real-time 3D environment feasible.

For example, the Sun Developer Network (41) developed a Grand Canyon terrain visualization by using fully the Java Programming language. A multiresolution render-
ing algorithm was used to avoid holding the entire data-set in memory at once, and uses memory mapped files, accessed via java.nio, to minimize data copying and heap size. The innermost rendering loop decimates the geometric data at run time while sending it to the graphics card uses java.nio direct buffers. The entire application, including the physically-accurate flight model and rendering loop, is written in the Java programming language. Figure 9 shows the images of Grand Canyon developed by this system.

Recently, Huirong et al. (42) demonstrated how 3D terrain visualization could be effectively visualized in a network-based environment by combining VRML and its specific rendering techniques. The system could be upgraded to the latest format of VRML, X3D. This will provide greater interactivity between the user and the system.

Martinez et al. (43) used VRML as an exponent of Web3D technology to analyze virtual terrain representation on the web. They found that VRML needs support from a graphic engine to overcome problems with handling the program (code). They suggested that Open-SceneGraph be used for graphic routines and the system was successfully implemented.

Ruzinoor et al. (44–46) have done extensive study on online 3D terrain visualization. The study included finding the best GIS software for online 3D terrain visualization, finding the best web servers for online 3D terrain visualization, and finding the best contour line intervals for online 3D terrain visualization.

5. Software for visualizing 3D terrain

Commercially available software, generic toolkits, such as precision visuals – workstation analysis and visualization environment, aydin visual solutions, and interface region imaging spectrograph (IRIS) Explorer can be used for the production of visual displays of different types of data. The generation of dedicated graphics software epitomizes the visualization revolution in computer graphics (47). Terragen (48) is a commercial package useful for photorealistic visualization of terrain capable of producing photorealistic professional landscape visualizations, special effects, art, and recreation designs. Figure 10 shows the 3D terrain image visualized by using this software.

The latest software developed by Autodesk (49) has the capabilities to create, manage, and analyze digital terrain models or surfaces. These tools are accurate and easy to use and create intelligent relationships between field and engineering data. Figure 11 shows the images of terrain visualizations created by AutoCAD Civil 3D.
The National Aeronautics and Space Administration (NASA) [50] has introduced open source software called World Win 1.4. This software lets the user zoom from satellite altitude into any place around the world. With the leveraging Landsite satellite imagery and shuttle radar topography mission data, World Win allows the user to experience the surface of the terrain. The 3D visualization gives the user a feeling of being in the place being visualized.

IRIS Explorer 4.0 is a powerful visualizing software for rendering the terrain. Figure 12 shows two sample of terrain image rendered by this software [51]. However, it requires powerful hardware, such as Sun or Silicon Graphics workstations. Less powerful PCs and Apple Macintoshes however have an increasing potential for visual display and can be used as effectively in developing new visualizations strategies.

As mentioned in the introduction, the popular online 3D terrain visualization is Google Earth [52]. Google Earth was released to public on June 2005 and Google Maps was released to public on February 2007. This geo-browser has capability on displaying the world in 3D (3D object and 3D terrain) but the accuracy of the terrain data is low only showing hilly areas and not fully covering the lower height areas. Other than that, there are limitations in this software since the interaction in the 3D visualization is only possible in fly through and not walkthrough mode. Figure 13 shows how 3D building objects, created using Google Sketch Up, are placed inside the Google Earth.

### Table 1

| Terrain Image | Type of Rendering |
|---------------|-------------------|
| ![Image](image1.png) | These results were visualised by applying only colour shading to the image. The image shows the highest peak and the lowest peak. |
| ![Image](image2.png) | These results were visualised by applying colour shading and contour. The image shows the highest peak and the lowest peak. |

Figure 12. Images of terrain visualization created by IRIS Explorer software [51].

Figure 13. The sample of 3D object on top of 3D terrain in Google Earth.

6. Discussion

The evolution of 3D terrain visualization started in the year 1982. Figure 14 shows the timeline for a review of 3D terrain visualization. The 3D terrain visualization has been divided into four sections; manual visualization of 3D terrain, automated visualization of 3D terrain, online visualization of 3D terrain, and software for visualizing 3D terrain. The second section is subdivided into photorealistic approaches, nonphotorealistic approaches, and real-time and nonreal-time approaches.

Until today, many techniques for 3D terrain visualization have been introduced such as molehill, hachure, hill shading, profile, pictorial, and block diagram. All these techniques are categorized as manual representations of terrain. The aforementioned techniques were developed between 1982 and 1995. Automated methods for visualizing terrain consist of techniques which can automatically generate terrain visualizations. The methods introduced between 1989 and 1997 are mosaic, profile, contouring, vertices, wiremesh, polygon model, and photorealism. Starting in 1997 until 2008, the techniques for photorealistic terrain visualization were introduced and developed. Some of the techniques combine algorithms (terrain and data), some combine nonphotorealistic and photorealistic techniques, and some deploy a multilayer hybrid approach. Beyond photorealism, other popular techniques among researchers were the NPR approaches. By implementing these techniques, terrain can be represented in black and white (without color) only in an artistic style. There are a few techniques seem to be better for representing the steepness of the terrain as compared to the photorealism. The techniques that can be categorized as NPR are watercolor, illustration, p-stroke, pencil, fog, luminance map, and silhouette. All of these techniques were developed between 1997 and 2004.

Since 1998, 3D terrain visualization has evolved dramatically. The first technique discussed how to solve the database problem for visualizing the 3D terrain. The other techniques continued to discuss multiresolution, LOD, geometry mipmap, geometry clipmap, and compression. All of these techniques work offline. The era of online 3D terrain visualization started when the 3D terrain visualization technique became popular. One of the reasons why these techniques are still popular is because of geo-browsers such as NASA World Win and Virtual Earth. The most important popular geo-browser among these is Google Earth. Some of the techniques used are quadLOD, tile, VRML, mobile, web services, ROAM,
and Java. A literature review shows that much research is still being carried out to solve problems in online terrain visualization, especially the compression problem. This is because terrain data are too huge for streaming online without splitting terrain data. Due to popularity of online and offline 3D terrain visualization, the software for generating 3D terrain visualization was developed, beginning in 1993. The software for 3D terrain visualization can be categorized as open source or commercial software. The software includes Terragen, Google, AutoDesk, NASA, IRIS, and Spaceyes3D. Some software can be operated both standalone and online such as Spaceyes3D. The most popular software is Google and their technology is updated frequently. At present, most Google users apply in their daily lives rather than professionally.

7. Concluding remarks
In conclusion, since the earliest map produced until now, rapid changes in the technology have occurred especially in the preparation of reliable 3D terrain visualization for GIS applications. 3D terrain visualization plays an important part in developing the GIS related applications such as 3D city models, urban visualization, town planning, tourism, military, and many more. If the data for 3D terrain visualization is not accurate, planning errors would result. With accurate data, however, 3D visualizations help decision-makers make better planning choices. 3D terrain visualization involves processing large datasets. Hence, many applications today focus on the processing aspect in order to aid real-time visualization. Users demand more realism on the 3D terrain visualization.

Figure 14. The timeline for a review of 3D terrain visualization (1982–2011).
tion. Thus, many researchers focus on improvements in this area. Some researchers also have developed NPR for representing terrain, such as silhouette rendering algorithm, p-stroke, illuminations, and other techniques. Due to emerging of mobile devices and improvement of internet technologies, many new systems are available to users such as Google Earth, Microsoft Virtual Earth, and NASA World Win. Currently the focus of many researchers is on mobile application of 3D terrain visualization. There are many problems to solve due to the large size of terrain data.

Notes on contributors

Ruzinoor Che Mat is working as a senior lecturer at the College of Arts and Sciences, Universiti Utara Malaysia. His major interests are GIS, precision farming, and precision agriculture. He has published more than six ISI papers and one book chapter.

Abdul Rashid Mohamed Shariff is an associate professor at the Faculty of Engineering, University Putra Malaysia. His major interests are GIS, precision farming, and precision agriculture. He has published more than 45 ISI papers and 3 book chapters.

Biswaject Pradhan is a faculty member at the Institute of Advanced Technology (ITMA), University Putra Malaysia and also a research member of Faculty of Engineering, UPM. His major interests are in remote sensing, GIS, data mining, and soft computing techniques in various earth resources applications. He has published more than 90 ISI papers, 3 books and 7 book chapters.

Ahmad Rodzi Mahmud is an associate professor at the Faculty of Engineering, University Putra Malaysia. His major interests are GIS and spatial modelling techniques. He has published more than 40 ISI papers.

Mohd Shafry Mohd Rahim is a senior lecturer at the Faculty of Computer Science & Information Systems, Universiti Teknologi Malaysia. His main research interest is computer graphics, 3D GIS, virtual reality, and terrain visualization. He has published more than 12 ISI papers.

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