

Computer-Aided Visualisation of Archaeological Caves

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Introduction

Historically the two most important methods of communicating the appearance and shape of a cave are cave surveying and cave photography, topics which have been widely reviewed elsewhere (Hatherley et al. 1987; Ellis, 1988; Stoddard, 1994; Wookey, in prep.). Computer-aided visualisation can use both these techniques as starting points to produce alternative ways of presenting the spatial information. These visualisations can be reproduced in print often allowing a greater degree of clarity or a more three-dimensional "feel" than can easily be achieved with the traditional methods. Alternatively, when reproduced electronically they can allow the viewer to interact directly with the visualisation which enhances interest and greatly improves the illusion of representing three-dimensional space on a two-dimensional plane. Some virtual-reality techniques can allow a directly perceivable three-dimensional representation which is the ultimate goal when trying to convey the appearance of a complex cave structure.

Visualisation is defined in the dictionary as 'to make something that is not visible to the eye visible to the mind' or 'to create a mental image'. Visualising scientific data is scarcely novel: people have been using pictures, maps and diagrams to represent information for a long time (including the representation of underground spaces: **Roe 2000**). The legend of Archimedes' death has him being slain by a Roman soldier while drawing geometrical figures in the sand. In the Middle Ages sailors were using astronomical charts with arrow plots of prevailing winds over the oceans to help navigate themselves around the globe.

Computer visualisation, also known as scientific visualisation, stems from the field of computer graphics. Computer graphics has been with us almost since the first digital computers and its origin can be traced back to the 1950s. In 1955 the SAGE (Semi-

Automatic Ground Environment) system was created to track enemy aircraft entering US air space during the Cold War. SAGE was constructed using computers built with 50,000 vacuum tubes which were integrated with radar systems to provide the first interactive computer graphics; operators could focus in on suspicious blips displayed on the screen by using a light pen.

Many of the basic concepts in early computer graphics were outlined in 1962 by Ivan Sutherland's PhD thesis on the 'Sketchpad' drawing system (Sutherland, 1962). This publication is widely regarded as the first to establish computer graphics as a technical discipline. A year later in 1963 Douglas Englebart invented the hand-operated pointing system called the mouse. Computer graphics continued to develop through the 1960s and 1970s. In 1974 the concept of computer graphics was popularised among the general public by an article in the widely journal *Scientific American* (Greenberg, 1974). Greenberg created an animated file called 'Cornell in Perspective' which used a geometric database to explore possible sites for Cornell's Johnson Art Museum. The term 'visualisation' was perhaps first made popular in a 1987 US National Science Foundation Report on scientific visualisation (McCormick et al., 1987). In this report the term visualisation was given the meaning 'high-resolution animation of time varying data'. It described visualisation as a powerful tool for scientists to demonstrate relationships that exist in their raw data.

One of the most exciting areas of computer visualisation today is Virtual Reality, creating a Virtual Environment (VE) in which a user can interact with external objects represented digitally. A VE can be defined as a three-dimensional, interactive, realistic, and real-time computer generated simulation. It provides direct input to the senses via devices such as a Head-Mounted Display (HMD), Binocular Omni-Oriented Monitor (BOOM) and DataGloves. One of the most effective Virtual Environments is the Cave Automatic Virtual Environment (CAVE) system (Cruz-Neira et al., 1993), developed by the Electronic Visualisation Lab, University of Illinois, Chicago. The CAVE is a 10-foot-square room, the walls of which are composed of rear-projection video screens. The CAVE itself is situated in a darkened lab in which projectors and mirrors overlap two images on each screen. Inside the CAVE, researchers wear stereoscopic liquid-crystal-shuttered glasses to turn the projections into hologram-like images. They have tracking devices situated on top of their heads and they carry small wand-like navigation tools. The CAVE was designed from the beginning to be a useful tool for scientific visualisation, and it enables researchers to see, touch, hear and manipulate data. Its goal was to help scientists achieve discoveries faster, while matching the resolution, colour and flicker-free qualities of high-end workstations. Another advantage of the CAVE is that it can be coupled to remote data sources, supercomputers and scientific instruments via high-speed networks.

This paper reviews the visualisation techniques currently available and provides examples of how they can be applied to visualising archaeological cave sites. Photography and surveying are the major sources of original data spatial locational data, although geophysical data can also be used as a starting point in some

circumstances. The techniques vary greatly in the amount of computational power that is required both to produce the original visualisation and, in the case of interactive visualisations, to display them, and we discuss the implications of this. Inevitably some techniques require specialised hardware or software to be installed on the host computer and in these cases the technique will only be described rather than demonstrated.

Survey Based Visualisation

Traditional surveys are usually portrayed as plan and elevation views (Figure 1). However the three-dimensional path of the centre line of the cave passage or its floor has usually been recorded and if this is combined with information about the cross-section at regular intervals then a fully three-dimensional model of the interior wall of the cave can be built up. This process can be greatly simplified using automatic tools to generate the cross section such as laser or ultrasound scanners (Sellers and Chamberlain, 1998; Robson Brown et al., 2001). The profile information can be entered directly into a suitable CAD package such as AutoCAD (AutoDesk: <http://www.autodesk.com>) or form-Z (auto-des-sys: <http://www.autodesys.com>) and a 3D surface constructed around the profiles using the various surfacing tools available in the CAD package.

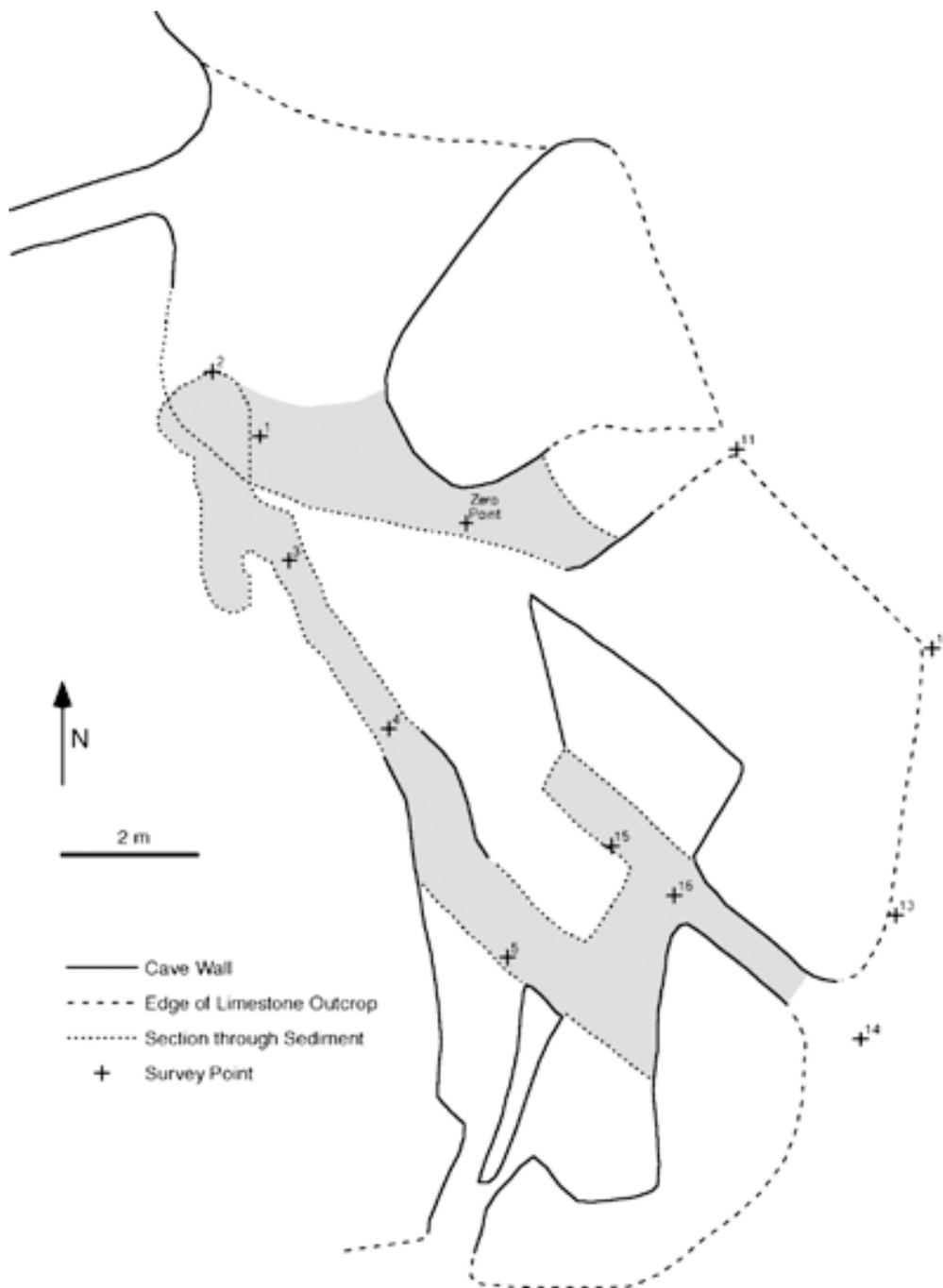


Figure 1. A traditional plan of Kitley Shelter Cave - a small archaeological cave [Sellers & Chamberlain 1998]
Note: stippled areas are portions of the cave system surveyed using an ultrasound scanner.

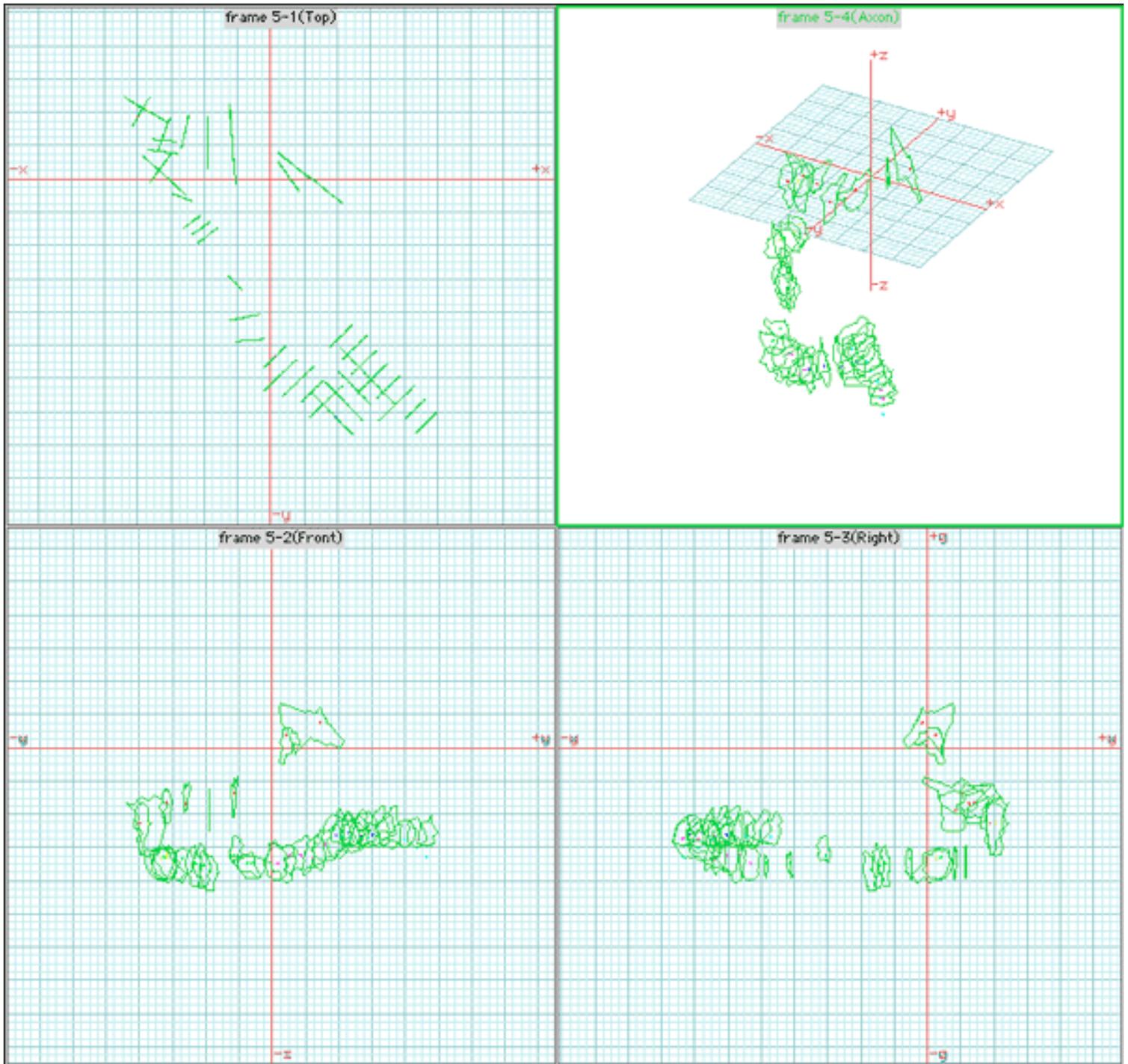


Figure 2. Model of Kitley Shelter Cave showing survey cross sections

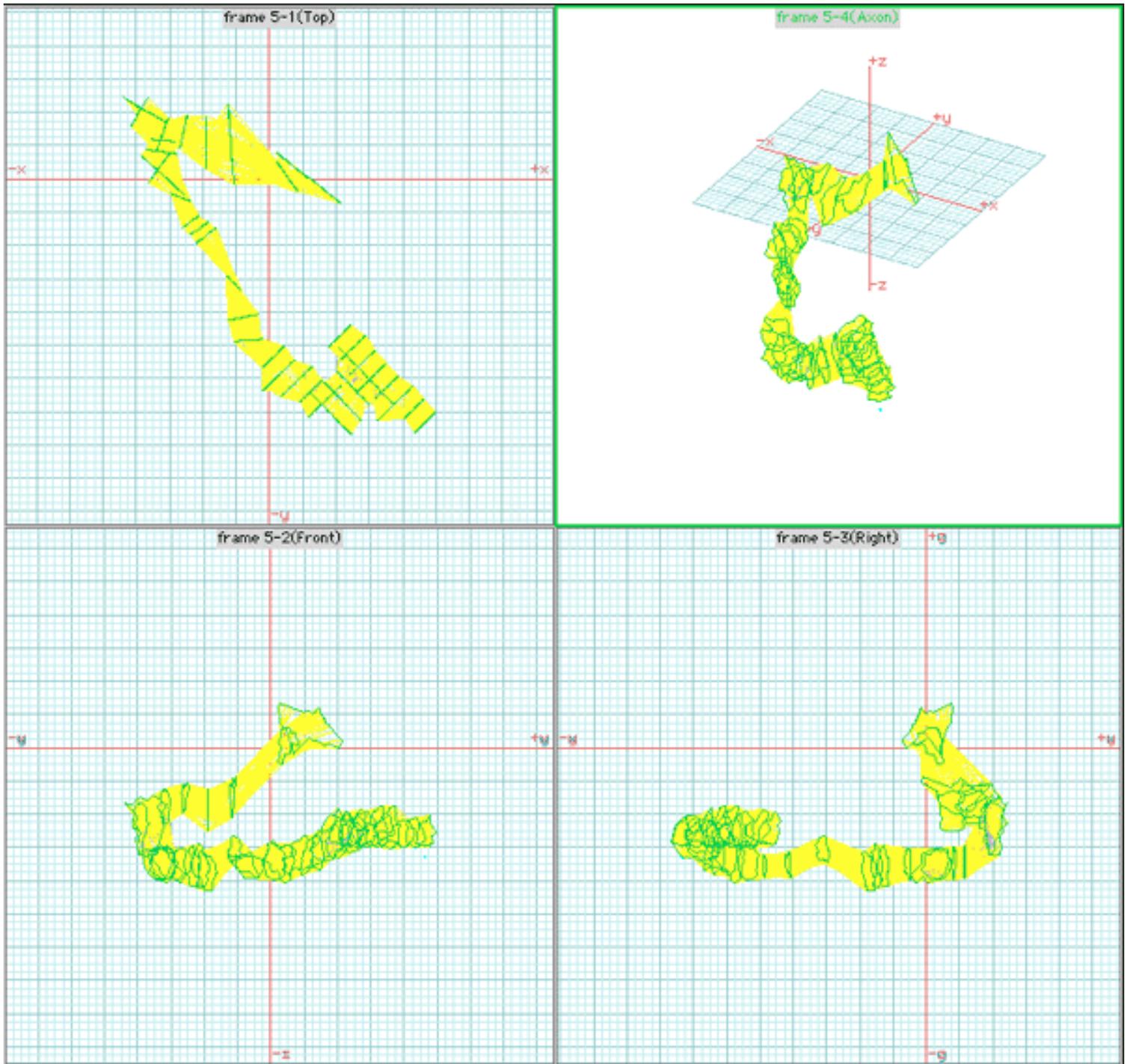


Figure 3. Model of Kitley Shelter Cave showing how the areas between the cross sections can be filled using skinning

Once the model has been surfaced then there are a number of options for dissemination. For printed production the publisher will require a high quality image of the structure. The CAD design records the shape of the cave only and so we need to artificially select a suitable colour and texture for the surface, choose a viewing direction, set lighting parameters and then allow the computer to produce a realistic

rendering of the cave. CAD programs are often not the best programs for producing this sort of realistic-looking image. In the example below the CAD model was exported from AutoCAD and converted into a form suitable for the Persistence of Vision ray-tracing package (<http://www.povray.org>). A view direction was selected and a stone type chosen from the material library available in the software package. The resulting rendering (Figure 4) is spectacular and effective, but this type of rendering is necessarily slow - certainly taking minutes if not hours to calculate.

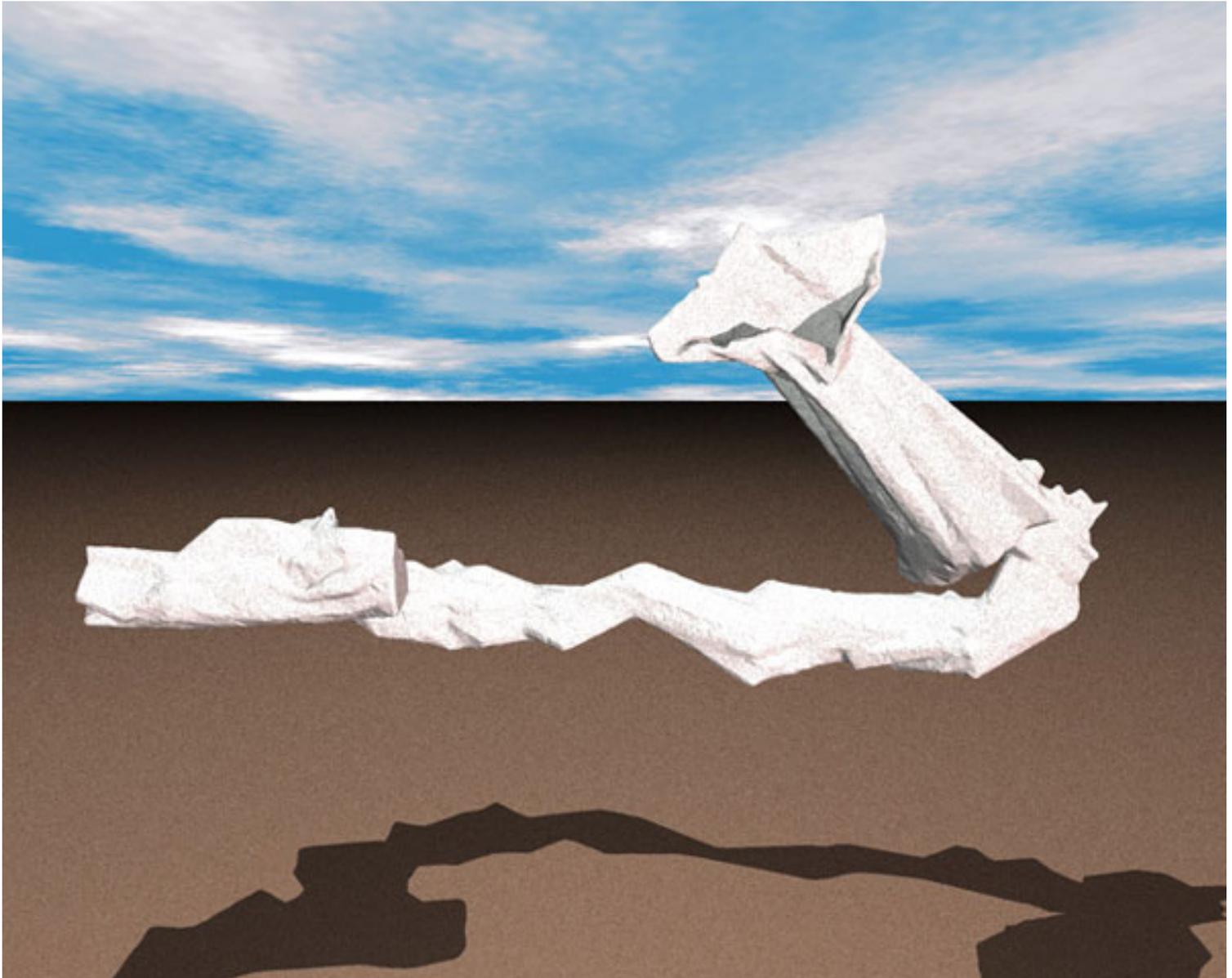


Figure 4. A version of Kitley Shelter Cave rendered using POV-RAY

For electronic distribution we could simply display an electronic version of the image. However this loses the key advantage of user interaction (real-time rotation and fly-through). There are two main approaches available and the choice depends

on the computer hardware available and distribution mechanism. The first option is to produce an animation based on a number of rendered frames of the 3D model taken from different eye positions. This can either be a fly-through with the eye position moved through the model as if the viewer was climbing through the cave or it can be a panoramic view that is treated much the same way as the panoramic views mentioned in the photography-based section (below). Producing the number of pictures required and converting them into a movie file is very time consuming but the end result is quick to display even on slow computers although it does produce large files which can be slow to download over the internet.

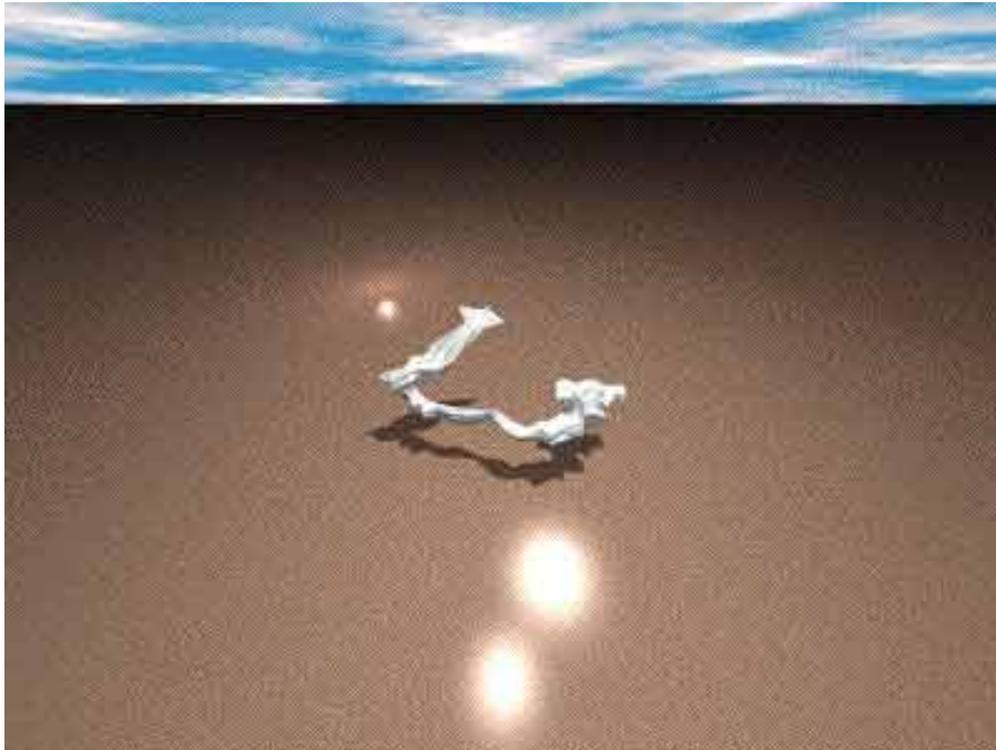


Figure 5a. A fly-through animation of Kitley Shelter Cave

Click on image to display the fly-through QuickTime movie. This movie is an 18MB file and therefore not suitable for slow internet connections.



Figure 5b. A fly-through animation of Kitley Shelter Cave

Click on image to display the fly-through QuickTime movie. This version has a lower resolution to reduce the file size to 1.8MB to make it more suitable for slower internet connections.

Note: Both versions require QuickTime.

The second option is to produce files in a 3D format that can be directly displayed by a browser plug-in and the most widespread option for this is to use Virtual Reality Modeling Language (VRML) (<http://www.vrml.org>). This option has the great advantage of producing relatively small files and can usually be created directly from within the CAD package. How well it is displayed and the speed with which it can be manipulated depend entirely on the capability of the viewer's computer. The VRML format has the advantage of allowing the viewer to interact with the 3D model itself so that the viewer can perform accurate measurements and alter lighting and surface parameters that affect the appearance of the model (though not its shape).

Geophysics Based Visualisation

Geophysical techniques such as ground penetrating radar, seismic profiling, resistivity tomography and microgravity can be used to map out the three-dimensional shape of subterranean structures such as caves. In their simplest form these techniques produce a two-dimensional vertical slice along a surface transect. However, unlike surface geophysical mapping there is usually a great deal of post-processing required to produce these vertical slices as the information is not simply the representation of raw signal strength that is commonly used for surface horizontal plane geophysical maps. These two-dimensional planes can usefully be displayed as contour maps or pseudo-coloured intensity maps using programs such as MATLAB (The Mathworks, <http://www.mathworks.com>).

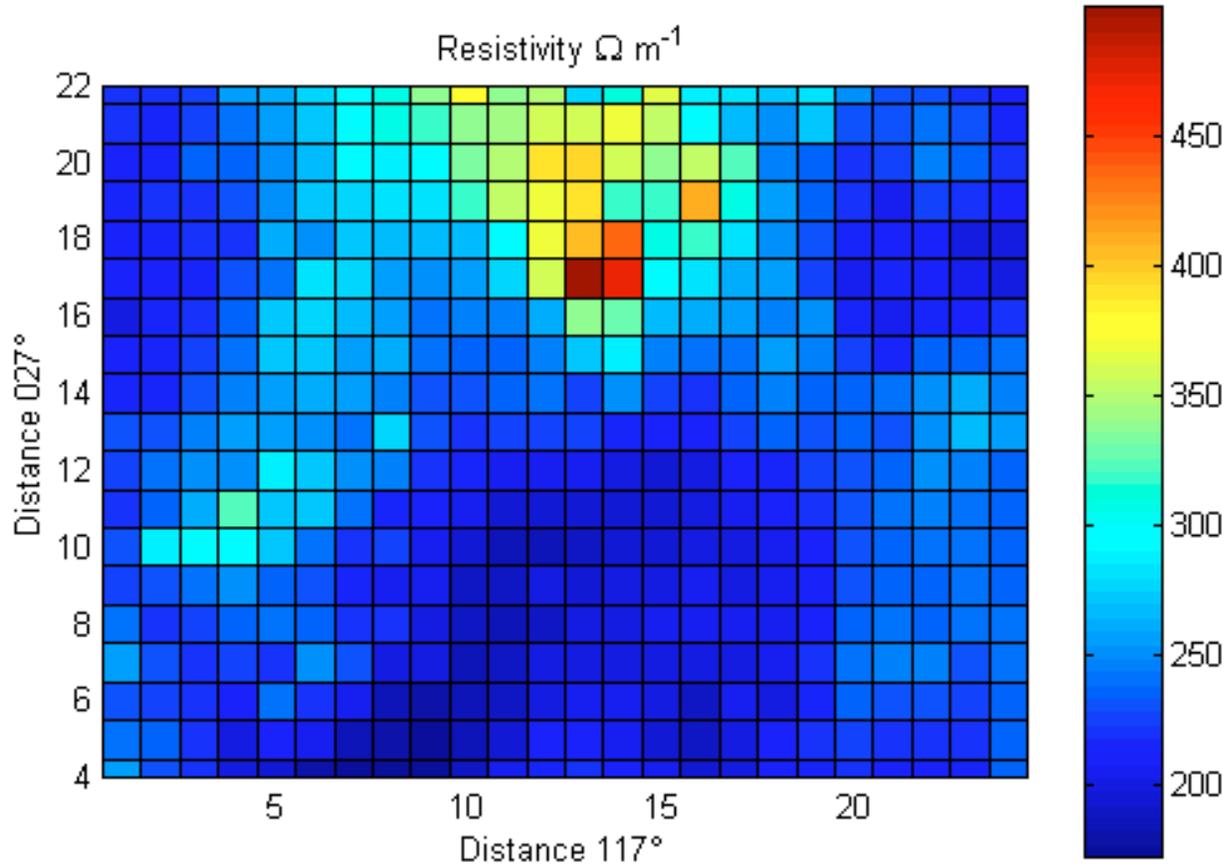


Figure 6. A pseudocoloured resistivity plot produced using Matlab

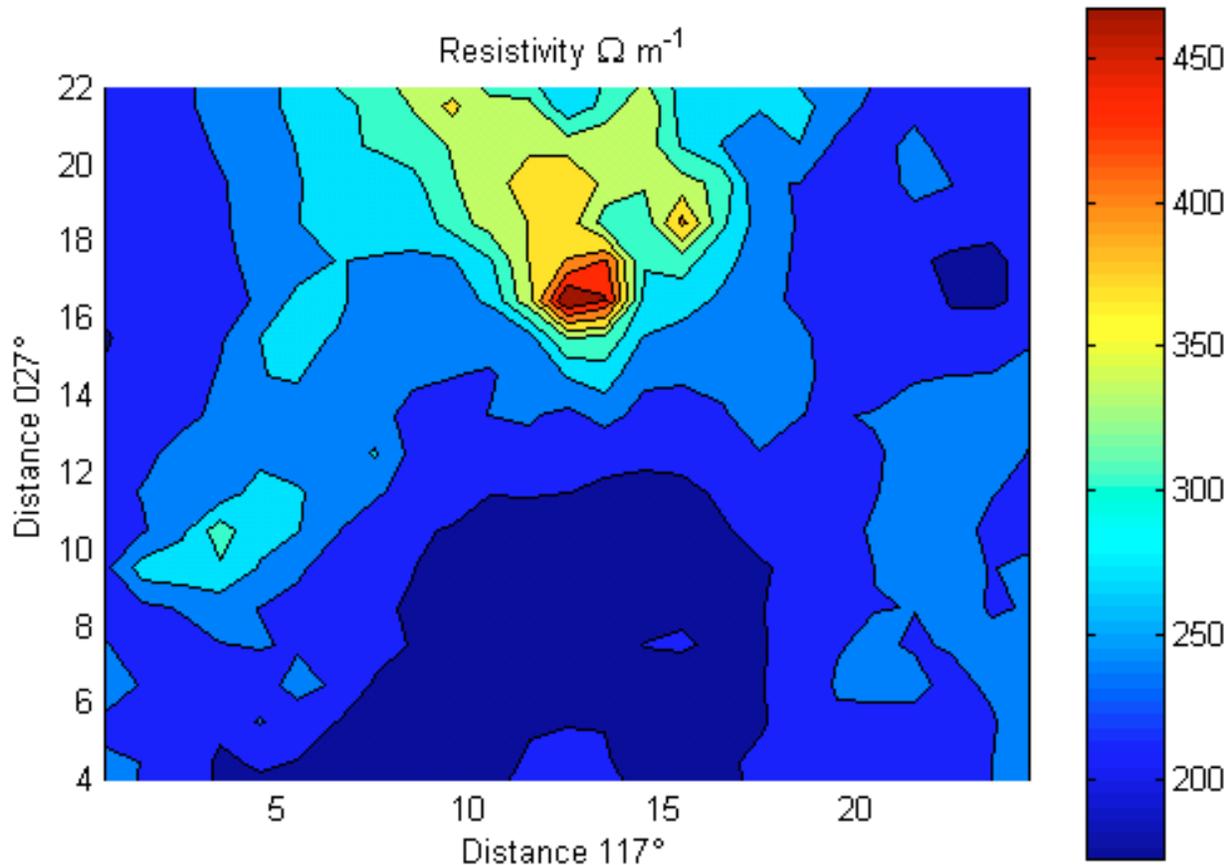


Figure 7. A contoured resistivity plot produced using Matlab

By taking multiple vertical slices of subsurface topography a complete three-dimensional volume can be defined. The resulting dataset is very similar in concept to the data produced by a medical X-ray Computer Tomography (CT) scanner and a great deal of research has been carried out into methods of portraying such data. These datasets are called voxel datasets: the data are treated as a set of cubic building blocks stacked in a 3D array. They can be visualised by ray-tracing -in this case each block is treated as if it were made of coloured glass with the opacity and intensity of the colour set by the signal strength in the block. This produces the rather hazy effect shown in Figure 8. This form of imaging is again a slow process and so only suitable for producing single images for printed publication or VR-movies for simple interaction. To allow for rapid rotation the voxel model needs to be converted into a CAD style surfaced model represented in VRML. This is done by a process called iso-surfacing which is a direct 3D equivalent of drawing contour lines. MATLAB will again accomplish this or the Visualisation Toolkit (VTK by Kitware: <http://www.kitware.com>). The endresult is once again a relatively

small surface model that can be treated exactly as you would treat a CAD based cave model.

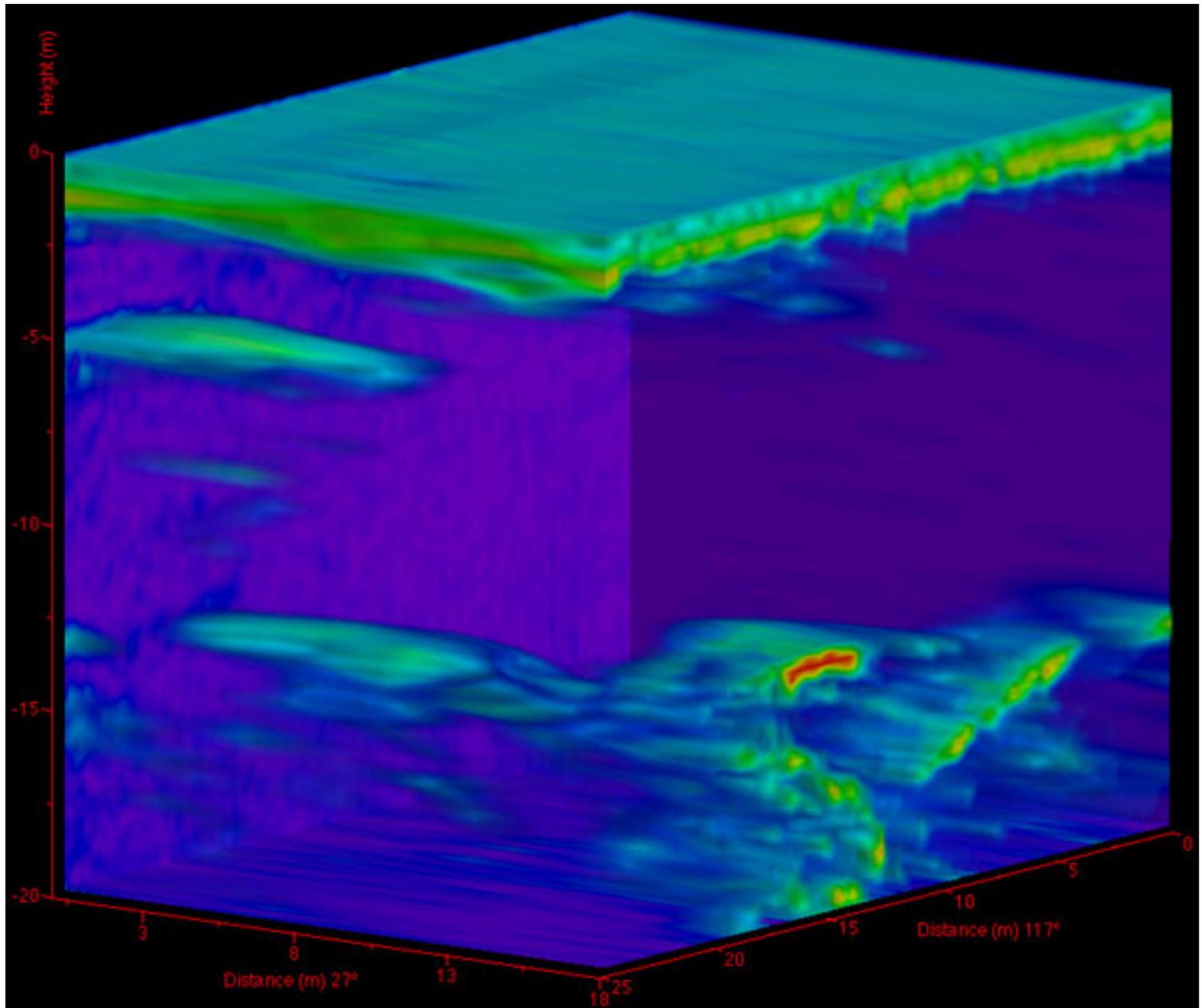


Figure 8. Ray-traced GPR image produced using Noesys (Fortner Research <http://www.fortner.com>)

Photography-Based Virtual Reality

In theory by taking a sufficient number of photographs from known points and in known directions within a cave, a complete representation of the interior surface can be built up by stitching together the frames and removing the areas of overlap. This surface representation can then be viewed using software that displays the appropriate part of the surface for an observer standing and looking arbitrarily within the cave. The end result is spectacularly realistic and depends ultimately on

the quality of the original photographs. It can be viewed on relatively slow computers but can require a large number of original photographs and works best when a reasonable amount of care has been taken sighting and orientating the camera as well as illuminating the scene. The file size produced by the so called 'VR-movie' can also be large if the picture quality is reasonably high. There are several competing technologies (e.g. PhotoVista and RealityStudio from MGI Software: <http://www.mgisoft.com>; QuicktimeVR Authoring Studio from Apple Computer: <http://www.apple.com>) but the basic procedure is the same for all of them.

The first step is to decide where the photographs are going to be taken from. For a true walk-through experience a number of positions need to be chosen throughout the cave complex, but for a simple panoramic view a single position inside the cavern is all that is required. For a walk-through the positions will need to be marked on a cave plan so that the software can join up the views intelligently later.

The second step is to take the pictures. This will depend on the geometry of the cave but ideally the pictures should be taken with a fairly wide angle lens camera mounted on a tripod with an angle calibrated pan head and a spirit level to ensure it rotates in a horizontal plane. A number of photographs should then be taken panning through 360° allowing approximately 1/3 to 1/2 image overlap. This translates to approximately 18 images (taken at 20° intervals) for a 28mm lens on a 35mm camera. Photograph number and orientation will need to be recorded carefully if multiple panoramas are going to be linked up but this is less important if isolated panoramas are recorded in each cavern. Accurately aligned photographs will produce distortion free panoramas but even images taken with handheld cameras can be successfully stitched together although it is very difficult to eliminate all distortion between images taken in this way. As in all cave photography, good lighting is key to getting professional looking results: and 360° even lighting can be difficult to achieve. Having a motor drive on the camera makes it very much simpler to avoid misalignment between photographs, as does using a good, sturdy tripod.

Each image then needs to be transferred on to a computer. If a digital camera has been used this step is straightforward, but if a normal roll film camera has been used the quickest option is to use Kodak's PhotoCD service which produces a CD-ROM containing scans of all the photographs on a roll of 35mm film. Alternatively the film can be developed as normal and the individual photographs scanned into the computer using a desktop scanner. The images are then stitched together using the stitching software and the VR-movie file is produced. This process is computationally intensive and requires a reasonably powerful computer.

VR-movie files are viewed using specialised viewing software. Quicktime from Apple Computer available for Macintosh and Windows computers runs either as a standalone viewer or as a plug-in for a web browser. A plug-in is also available to view MGI movie files. As can be seen from the example, the image is visually attractive and compared to the other methods it is reasonably quick and easy to

produce. It is not however completely flexible since the view position is preset and sometimes the viewer does not have control of the elevation of the view direction although you do in the Creswell example in figure 9. It is also impossible to analyse the visualisation quantitatively. The designer can specify hot-spots within the view that define areas of interest. These can be enlarged or can be used to trigger other multimedia events such as text messages or audio commentary.

Any of the previous visualisation techniques can take advantage of the VR-Movie technique to allow pseudointeractive viewing on a relatively low-powered computer. The original panorama can be created by producing a series of images from different points of view and these can be stitched together and displayed using the standard VR-Movie viewer. This is very useful when highly computationally expensive rendering is being used such as ray-tracing since it is very difficult to produce real-time rotation from the original data.



Figure 9: Robin Hood's Cave, Creswell Crags

Click on the image to access the Creswell Crags virtual tour illustrating the use of VR-Movies for cave visualisation.

Stereoscopic Rendering

The techniques described above used techniques of shading, perspective and movement to cause the appearance of 3D depth on a 2D display. However the

image is not fully realistic because each eye is presented with the same information. We can go one step further and use a technique known as binocular parallax to further enhance the 3D effect. For this a separate image needs to be displayed for each eye and this generally requires specialised (although not necessarily expensive) hardware.

The easiest option is to render the CAD model of the cave as two images seen from two slightly different directions. These can be displayed in contrasting colours (usually red and green) with the observer using colour filtered spectacles to ensure that each eye only sees one of the images (Figure 10). These glasses are very inexpensive (although not widely available) the effect is impressive. The disadvantage is that any colour information in the original scene or model is lost, since colour is used to define the eye-specific image. For printed media this can be overcome by producing two separate coloured images that can be viewed with a stereoscopic viewer. Stereoscopic viewers require images to be a particular size so this technique is impractical for computer use where the image size at the user's end is not known (and holding a stereoscopic viewer up to the computer screen would be impractical). A similar effect can be generated by using special glasses with LCD screens where the view for each eye is blanked in synchrony with flashing two alternate images on the computer screen. An alternative approach is to build two very small screens actually into the glasses themselves. Both these methods are extremely effective but currently require expensive hardware.

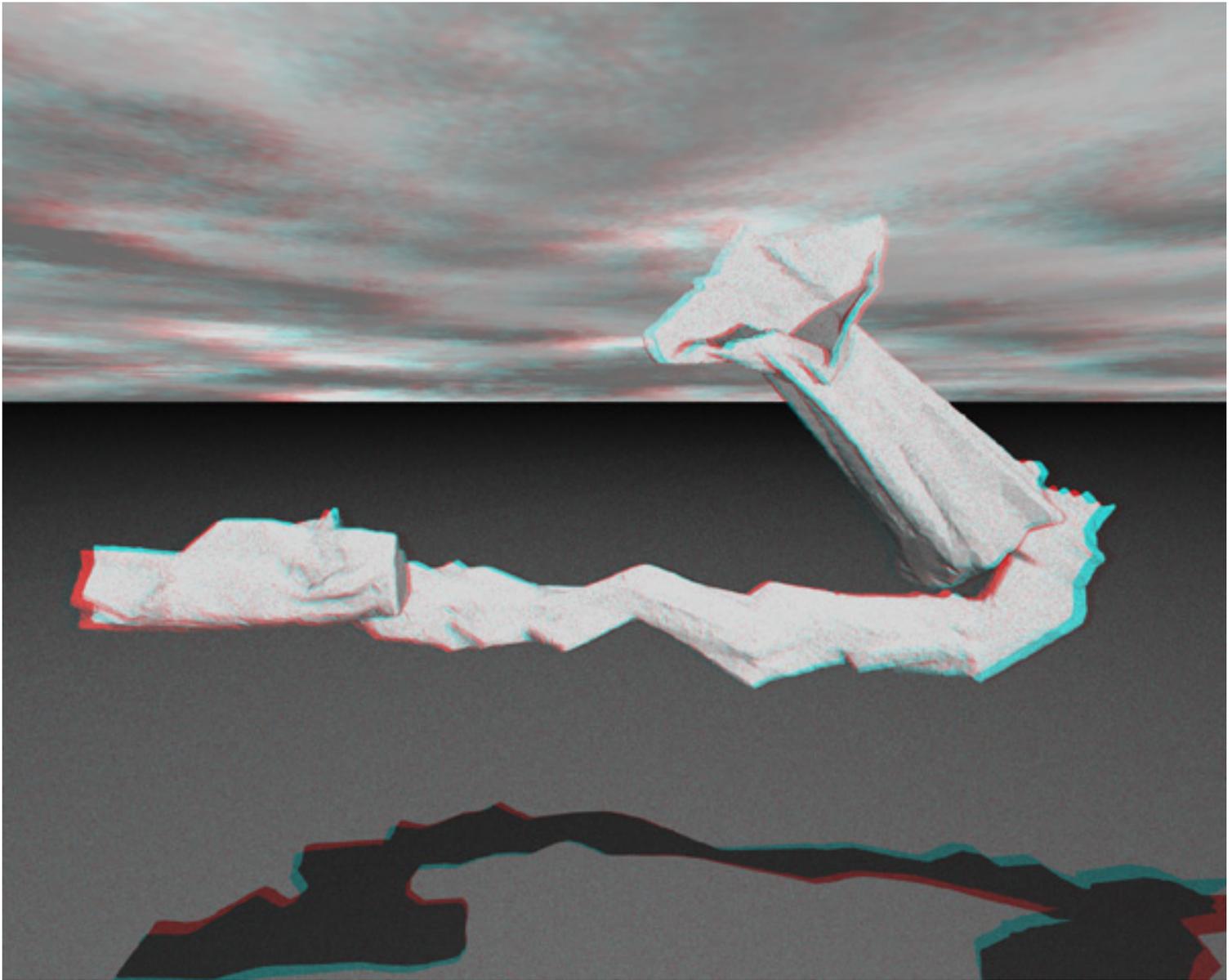


Figure 10. 3D view of Kitley Shelter Cave. Needs to be viewed with a red filter over the left eye and a blue filter over the right eye.

3D Solid Modelling

One of the most satisfying but unfortunately the most expensive way of representing the three-dimensional shape of a cave is to produce a physical 3D model. This can be sculpted from photographs and surveys in the traditional manner but most of us have neither the skill nor the time to do this. There are however several automated ways of producing models based on CAD data. These are known by the generic term of 'Rapid Prototyping' since their main market is the production of prototypes of engineering designs that can be used as masters for mould productions or as samples for marketing. This is an ongoing area of research, and here we provide brief descriptions of some of the current commercial processes.

Fused Deposition Modelling or FDM (<http://www.stratasys.com>) where a robot driven extrusion head deposits a fine plastic filament at precise 3D locations and builds up the model 'string by string'. Laminated Object Manufacturing or LOM (<http://www.helisys.com>) uses a laser to cut cross sections from thin foil which are glued together in stacks to produce the required model. Selective Laser Sintering or SLS (<http://www.dtm-corp.com>) again builds up a 3D model layer by layer but this time the base is a powder that is fused by the laser rather than sheets that are cut by a laser. Stereolithography or SLA is another variant where lasers are used to cure a liquid polymer to generate the required 3D form (<http://www.3dsystems.com>). These are all very expensive techniques but they do produce beautiful models. There are some cheaper but less precise options coming on the market which are collectively referred to as 3D printers (e.g. <http://www.solidimension.com>) which should make this a more affordable option. It is likely that as costs fall these techniques will find many useful applications in archaeology.

Future Directions

For centuries scientists and engineers used illustration and drawing to visually depict their ideas. Computer visualisation techniques have quickly become an active area of research and development. Early visualisation applications generally involved large-scale interpretation of visual data, such as medical tomography, satellite imagery, and scientific data reduction. The techniques of visualisation are now being applied to many more fields of research and commerce. This trend has been driven by visualisation algorithms themselves and increasing computing capabilities, which allow for more complex analyses to be performed. Today, the move towards further real-time 3D graphics display capabilities is helping visualisation become part of a more interactive approach to scientific data analysis. Computer visualisation involves more than computer graphics illustrations. It includes generating abstract computer imagery from data-intensive computer simulations or massive repositories of scientific digital data. The future of visualisation will only be limited by the imagination, resourcefulness and ability of researchers and users, and computer visualisations created today will appear as child's play by 2025.

Virtual reality may be one of the most important technologies in our future, producing a great leap forward in many fields. Since human beings are primarily visual animals, we respond much better to spatial, three-dimensional images than we do to flat, two-dimensional text and sketches. With three-dimensional images like those produced in virtual reality, we are better able to see patterns, relationships, and trends. Virtual reality goes beyond static images to ones that we can navigate through and interact with in real time, enabling us to look at things from any perspective.

Currently there exists a potential threat to the usability of virtual environments: some users experience discomfort during a session in a simulated environment. These reactions have also been observed in driving and military flight simulators,

and the phenomenon is called 'simulator sickness' (Kolasinski, 1995). Simulator sickness is a form of visually-induced motion sickness, induced by the eyes telling the mind that the body is moving, while the other proprioceptive and cochlear senses are telling the mind that it is not.

The future is not a set place and therefore it is impossible to know for sure what we'll be using virtual reality for in the future. With virtual reality the images are more detailed, the animation more believable, and the sound effects are more atmospheric. The potential of virtual reality is enormous. Real-time images are not far away, neither is 3D sound, the ability to make a noise seem to come from any point in space. True 3D images that do not induce simulator sickness will be next, and with them will be affordable head-mounted displays that extend to peripheral vision, with microphones and earphones built in. Today's cumbersome datagloves will be replaced with something more light-weight and flexible, with the ability to induce sensations such as texture and temperature, this can then be taken further to entire body-suits. There is also the possibility that someone may develop a safe, reliable means of making digital connections to human nerve cells. Instead of trying to fool the body's senses, they are simply bypassed by connecting your computer directly into the nervous system.

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