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C.I.S.R.G. DISCUSSION PAPER 19

Towards Sketch-based Exploration of Terrain : a feasibility study

by

P-L Lesage and M Visvalingam

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1. Introduction

The Cartographic Information Systems Research Group (CISRG) of the University of Hull is keen to revive interest in the dying art of landscape sketching and re-stage it on today's reactive and dynamic computer technology (Visvalingam, 1999a). As Gestalt psychologists have shown, the perceptual system is adept at organising sparse cues into potentially meaningful forms (Hochberg, 1964). This is especially so when images are animated. An often-used illustration is that of the spontaneous recognition of a Dalmatian dog emerging from frames of scattered spots when they are animated. However, demonstrations such as this and other animated sketches on TV are often contrived to succeed. Northrup and Markosian (2000) noted how the lack of inter-frame coherence in real time animation of silhouettes could be distracting. In scientific applications, there is also a need to abstract other form defining cues from a grid Digital Elevation Model (DEM), also known as a height field. Dowson (1994) and Visvalingam and Dowson (1998) found that it was possible to extract static 2D sketches using Visvalingam's algorithm (reported in Visvalingam and Whyatt , 1993); Figure 1 provides an example of their P-stroke sketch. However, Visvalingam and Dowson (2000) found that similar sketches, based on the Ramer (1972)/Douglas-Peucker (1973) algorithm, were not as successful. The graphical primitives were misplaced and did not bond too well into a coherent sketch. Even where the marks cohered into an easily perceived sketch, the outcome was misleading. Disciplines concerned with other forms of abstraction, such as statistics (Moroney, 1951) and cartography (Monmonier, 1991), are well aware of the scope for unintentional distortion.

Sketches facilitate visual processing of static images by focusing attention of the more significant features. Animated sketches can expedite browsing of voluminous surface data on remote sites on the Internet. The omission of redundant information also frees up surface space for the inclusion of the main themes being investigated. These include patterns of land use, resource potential, tourist attractions, proposed developments for environmental impact analysis, battle plans and hazards; Dowson's PhD project (1994) was motivated by the requirements of a civil engineering consultancy (Visvalingam and Dowson, 1998). Maps in their role as sources of information also need to include much textual content (Visvalingam, 1990). As such, research on sketching complements the superb achievements of photorealism (Fairclough, Online); and, more recent use of map information to place pictorial symbols, such as trees generated with L-systems, within painted visualisations of landscape contrived for environmental impact analysis (Wooley, Online). These trends and other background information may be found through the web record of an exhibition on "Art in Scientific Visualization of Terrain Data" held at the UK Royal Institution (Visvalingam, 1999a).

This feasibility study was mainly concerned with exploring whether frames of sketches, automatically abstracted from DEMs, would form smooth and usable 3D animations which invoke a clear perception of the solid mass defined by the surface. It explored whether sketches, consisting largely of occluding contours and surface creases, could be abstracted from luminance maps with a minimum of fixed lights for an entire movie. Image processing of luminance maps were explored since, as explained below, published work based on z-buffers do not appear to abstract significant internal edges detected by Visvalingam and Dowson (1998). Lesage (1999) created a conventional graphics environment to visualise the DEM, to explore lighting conditions and to project luminance image maps. The sketches were derived from the projected luminance image of the DEM using a few widely known edge detectors and the results were compared. Comparisons were also made with the P-stroke sketch.

The Sobel and Canny operators were selected to drive the automatic generation of frames for AVI and mpeg videos using just one, and later a combination of separate sketches for two, light sources. The resulting mpeg videos, posted on the web, demonstrate that it is possible to produce appropriate animations of the 3D mass of irregular terrain. Lesage (1999, 2000) provides a detailed account of his MSc project. This paper discusses his results within the broader context of image processing and Digital Cartography. The paper starts with a brief background which explains the reasons for basing the sketches on luminance maps. An overview of the sketching pipeline is then presented together with a description of the stages involved. The study was not immediately concerned with efficient abstraction of sketches for real time animation, nor with the identification of the best process for abstraction at this stage. Nevertheless, some limitations of the luminance-based approach and of the operators tried are highlighted. The wider implications of the results are then discussed. Some directions for future research are indicated in conclusion.

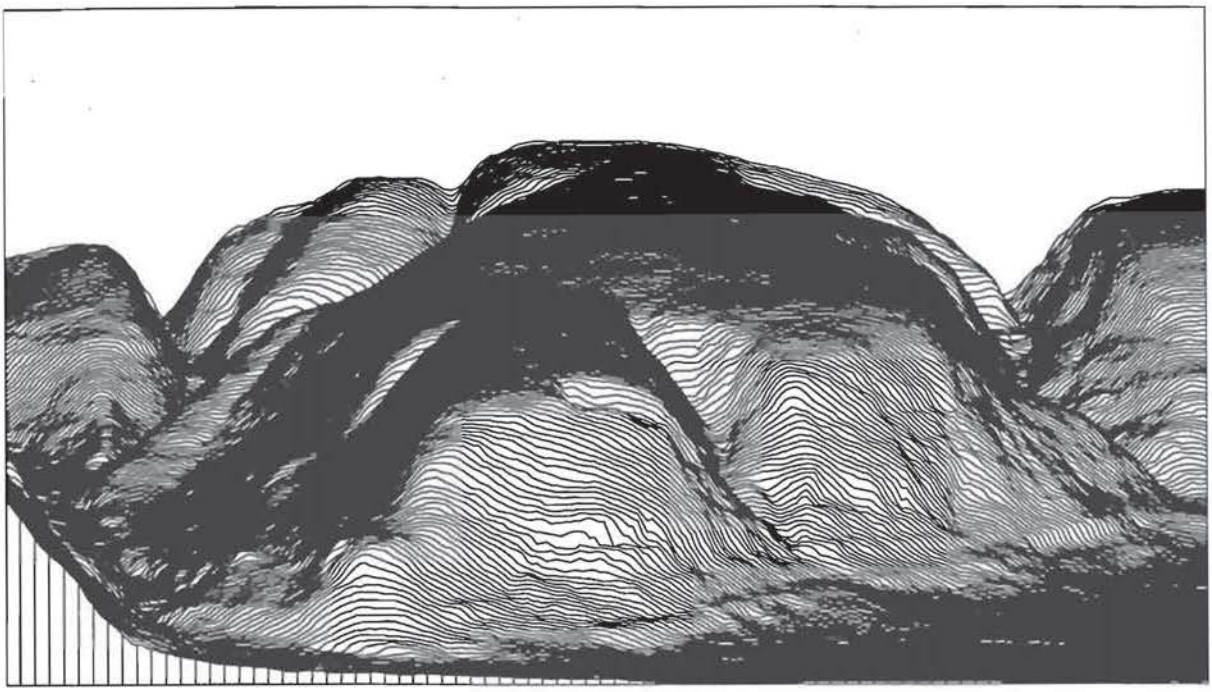
2. Data-driven sketching

Until relatively recently, mainstream computer graphics has focused mainly on the challenge of simulating photorealism. Now that this aim has been largely realised, others have found the emulation of sketching and illustration techniques equally challenging (see Visvalingam and Dowson (1998) for some early work in this area). Foley (2000) thought that this was more difficult because sketching deals with the semantics, and not just the geometric appearance, of the information being conveyed. He advised that "When we want to create an abstraction that conveys key ideas while suppressing irrelevant detail, we need to draw on the less-quantified tools of perceptual psychology and cognitive psychology, and the vast knowledge of cartographers and animators. An exciting challenge! (p 67)".

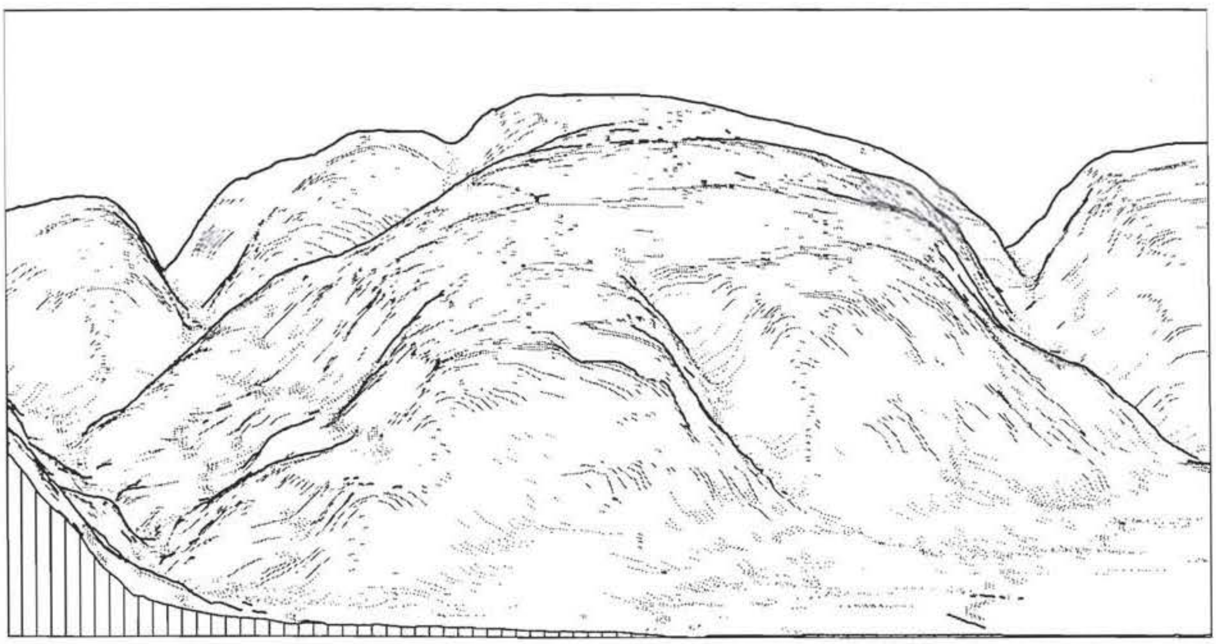
Unfortunately, many of the artistic techniques used for relief representation, such as the drawing of pictorial block diagrams (Lobeck, 1924) which were especially used in geology, are no longer widely taught by the Earth Sciences. There is an increasing reliance on Geographical Information Systems (GIS) which offer both image processing and Cornputer Graphics tools (such as for altitude and hill shading, for contouring, for plotting profiles and meshes, and for photorealism). Visvalingam and Dowson (1998) noted that these were classed as methods of quantitative relief representation in cartography. Qualitative depictions of terrain provide a visual impression of relief through a variety of pictorial methods. The construction of pictorial techniques involves the recognition of 'skeletal lines', which bring out relief features such as watersheds, stream networks, breaks of slope, ridges and edges of terraces (Imhof 1982, p 105).

Since the identification of such geographic entities is still the subject of continuing research, Visvalingam and Dowson explored whether DEMs may be automatically sketched without such semantic knowledge and form lines. They found that Visvalingam's algorithm for line generalisation is useful for eliminating unnecessary height information and for identifying the DEM cells located on significant relief features. These locations can then be depicted in various ways. Visvalingam and Dowson showed that rough, but pleasing, sketches can be created by simply extending these cells in profile, using different rules and symbolism, to create profile-stroke or P-stroke sketches. Even these simplistic sketches are better than many hand illustrations found in several textbooks but are poor in comparison to the drawings of past masters of the art. A few examples of these inspiring drawings which illustrate different techniques are included in Visvalingam (1999a).

The P-stroke sketch is still in the realrns of minimal simplification and only involves profile filtering. It is entirely mechanistic in much the same way that the early stages of low-level vision were believed to be entirely data-driven in Marr's (1982) theory of vision. Marr's analysis of the architecture of low-level vision is still the most popular even though there are competing algorithms for articulating his theory (Bruce et al, 1996). Marr and his co-workers believed that the early vision system abstracts, from the retinal images, scale-dependent descriptions called primal sketches. The latter are then compiled into a 2.5D sketch, which was thought to represent the final outcome of the early, data-driven stages of visual perception. Scanned images of real scenes normally form the input for such image processing. However, vision scientists often use contrived drawings and images in psychological experiments (Bruce et al, 1996). Sketches of terrain have also been derived by processing images of models and not just images of real scenes (see below).



(a) All Data



(b) P-stroke sketch with occluding contours
Source : Visvalingam and Whelan (1998), reprinted with permission from Elsevier Science.

Figure 1 : P-stroke sketch with occluding contours

Whereas the 2.5D sketch was output for automatic recognition, cartographic sketching is designed for human information processing and need not provide a full topological description of the landscape. The segmentation of terrain surfaces forms a related but separate strand of research within the CISRG. Also, cartographers are not concerned with the representation of perceptions per se but rather with the symbolic depiction of interpretations of data; maps and sketches are regarded as formal precept-based constructions. Even the rudimentary P-stroke sketch portrays inferred breaks of slope where the surface curves gently from the plateau top into the valley and where there are no distinct breaks of slope.

The P-stroke style is just one of many styles of cartographic relief representation (see Imhof, 1982; Robinson et al, 1995); it was inspired by a style of planar maps, known as inclined contour maps, originated by Tanaka (1932) and further refined by Robinson and Thrower (1957) and Dickinson (1969). The P-stroke sketch was contrived to study the scope for landform segmentation and for extracting scale-specific form lines. It is inherently unsuited for use in a 3D browsing system. This approach, being model-centred, does not provide a complete sketch since it lacks view dependent enhancement cues, such as occluding contours. These are included in Figure 1 by Visvalingam and Whelan (1998). If occluding contours are defined as the locus of points which mark discontinuities in depth along the line of sight, they miss some of the crease lines which people perceive as similar to occluding contours (Visvalingam and Whelan, 1998).

Occluding contours, on their own, are sufficient for delineating the outlines of solid objects. Saito and Takahashi (1990) used a conventional graphics system to set object and camera parameters, to apply perspective projection and hidden line removal and to store image based 2D arrays, called G-buffers (geometry buffers). The G-buffers were accessed by the rendering stage, which consisted of parallel pipelines for a) physically based photorealistic shading and texturing, and b) artificial enhancement with sketches for perceptual and artistic reasons. Users were able to interactively explore the combination of different 2D images. The combination of occluding contours and internal creases, respectively derived by edge-detectors from the depth and surface normal buffers, yielded a very effective sketch for a machine nut. Promising results were obtained by applying the same combination to terrain but parts of the scene were not sketched appropriately. Even when shading was added, the landforms appear to float in space. Visvalingam and Dowson (1998) noted the same effect when concavities were omitted from the P-stroke sketch. Saito and Takahashi added height contours to the occluding contours and included hill shading. The latter helped to 'ground' the forms but contours can give a misleading impression of tilted landforms, such as the plateau in Figure 1. This appears 'peaked' in both hyposometric (altitude shaded) and isoline plots (see Whelan, 1997; and Macaire, 1996; respectively).

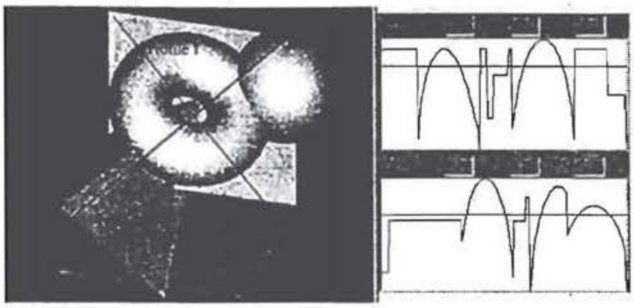


Figure 2 : Two luminance profiles for a geometric scene

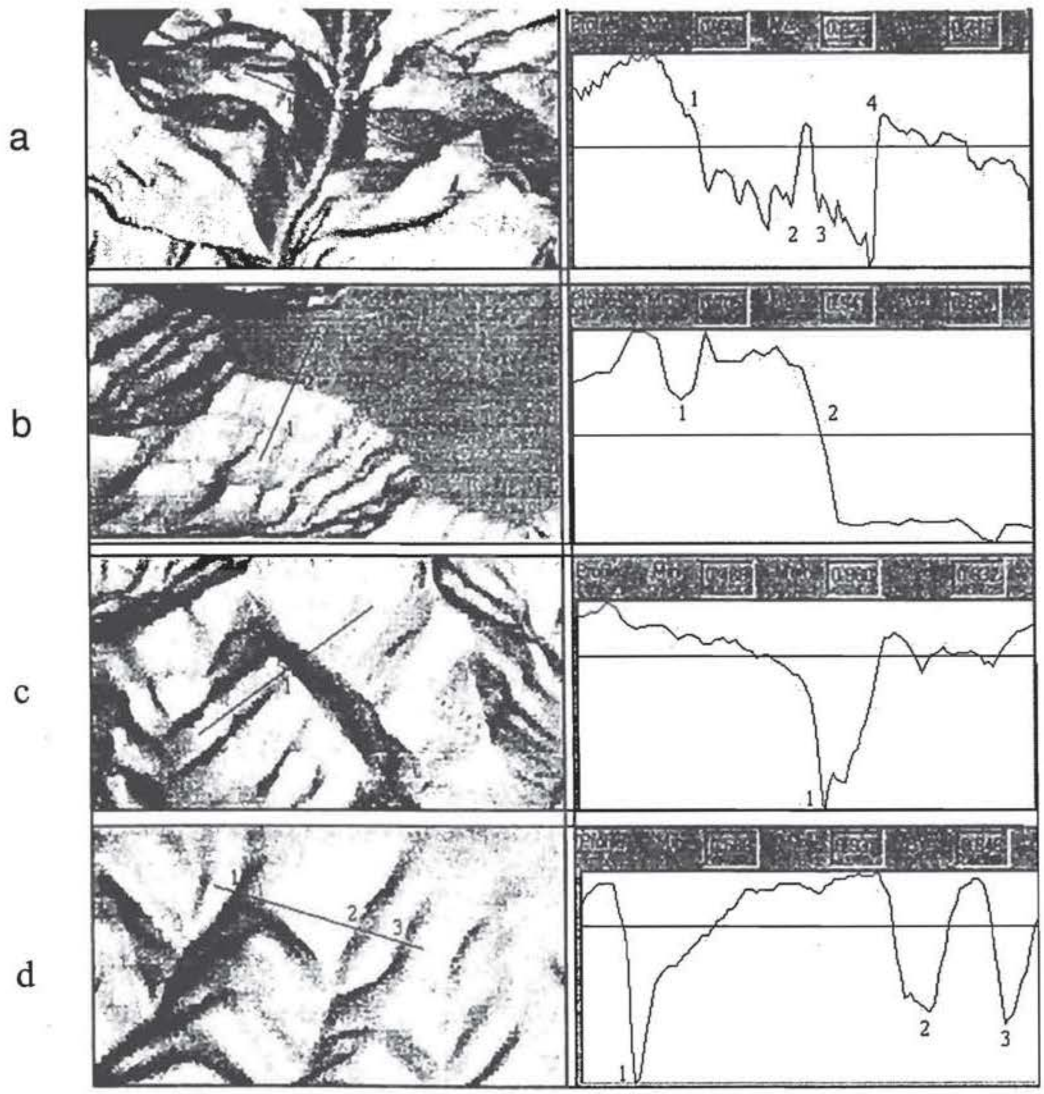


Figure 3: Luminance profiles of some important terrain features

a) a gorge and its sides; b) a plateau edge; c) a sharp ridge; d) some streams channels

Chang (1998) constructed an interactive system to experiment with combinations of other image operators, based on mean curvature, Gaussian curvature and the Laplacian convolution. The results for a machined and an irregular solid object were impressive, despite the presence of some artifacts. Northrup and Markosian (2000) noted that the 2D image-based approach does not accurately relate edges, such as the silhouettes that they were focusing on, to the underlying geometry but took advantage of the ease with which silhouettes may be image processed. In their hybrid approach, silhouette edges located on the model are processed in image space to extract the visible parts as long connected paths for stylised rendering.

The image-based approaches surveyed above arrive at a composite sketch by combining two or more 2D output images. Watt (1988) suggested that all types of occlusion and internal creases may be abstracted in one pass from luminance maps. Lesage (1999) therefore attempted to abstract better sketches containing both view and object dependent cues from luminance maps for animation.

3. Luminance maps

The description provided in this paragraph comes largely from Watt (1988, Chap 1). A single parallel, horizontal light source from behind the camera does not cast a shadow. Surface reflectance is thus a function of surface orientation. A uniform matte surface is provided by Lambertian reflectance. Watt used a simple example to illustrate how discontinuities in luminance variation reveal not just surface and self occlusion but also creases in the visible part of the scene. These discontinuities cause a peak and/or trough in the second derivative of the image luminance waveform. Whereas a luminance discontinuity causes a peak and a trough on either side of the discontinuity, luminance gradient discontinuities cause either a peak or a trough in the second derivative. Pearson and Robinson (1985) used the troughs in the second derivative of front-lit images to detect the parts that were slanting away from the light and camera to derive effective sketches of faces. The information conveyed by the peaks was not necessary for their application. Watt and Morgan (1985) adapted the use of second derivatives of luminance values to differentiate between occluding edges and all crease lines in the Mirage operator.

In Figure 2, discontinuities in the two luminance profiles show that it is possible to detect the edges of geometric objects. Similarly, luminance discontinuities in terrain surface also indicate breaks of slope. However, natural landscapes are very irregular and the creases are no longer step-shaped (see Figure 3) making it more difficult to detect edges. Even so, the discontinuities can be perceived in the luminance profiles.

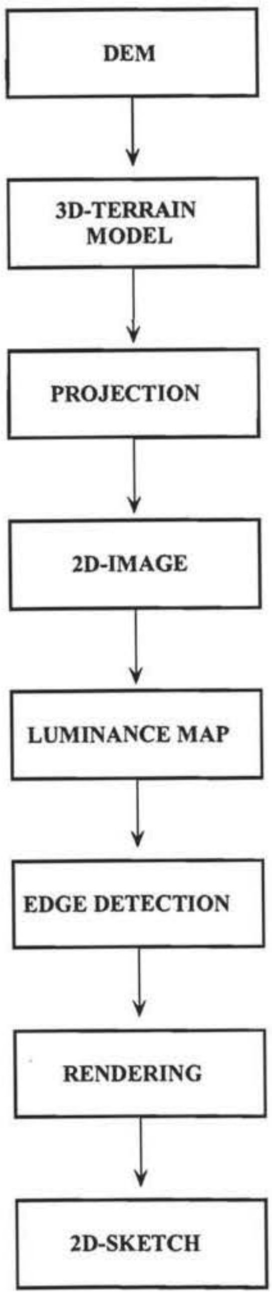


Figure 4 : Sketching pipeline

Figure 5 : Main window of sketching system

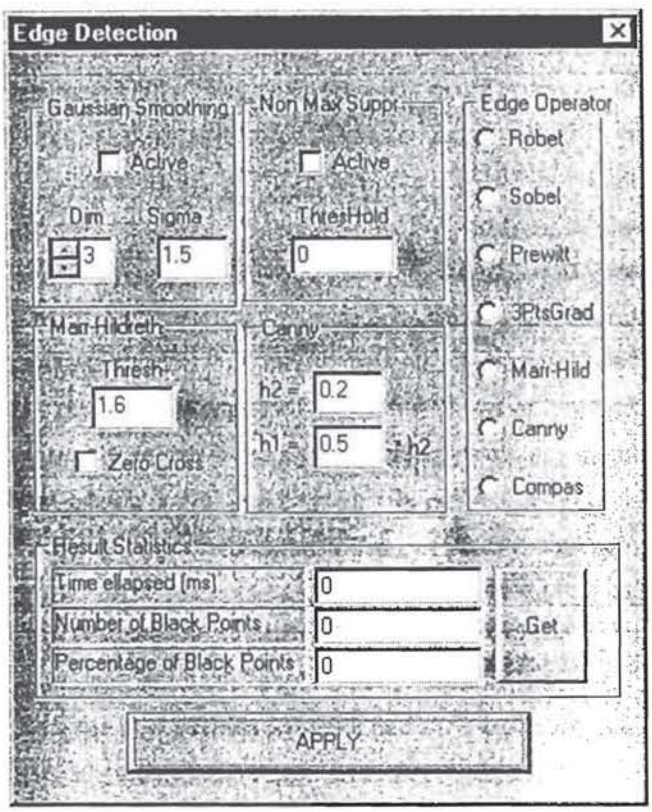


Figure 6: User interface for sketching

This project set out to ascertain the extent to which the traditional edge detectors were able to abstract appropriate sketches from luminance maps and to establish whether animated sketches induced the perception of the solid mass of terrain for future research on the superimposition of other information.

4. The sketching pipeline

The architecture of the sketching system is similar to those used by other systems based on 2D image processing, such as that by Saito and Takahashi (1990). The main difference lies in the use of a luminance map, rather than a z-buffer and surface normals, for edge detection. The sketching pipeline is shown in Figure 4. The Port Talbot DEM is a 10-metre resolution sample data set, made freely available by the Ordnance Survey of Great Britain. Visvalingam and Dowson (1998) selected this test data because it provides a challenge with its eroded and irregular plateau, and the fluvial and glacial deposits which mask the lower edges. The other DEM files used in this project, such as that of Crater Lake, were created by the U S Geological Survey (USGS). They cover dramatic landscapes which appeared to provide distinct edges optimal for sketching.

A conventional 3D graphics system was implemented using C++ (using Microsoft Visual C++ 4.0), the Microsoft Foundation Classes (MFC) for Graphical User Interfaces, and the OpenGL API with *glu* utility functions. OpenGL supports high quality 3D rendering and provides easy access to its various buffers for image processing and overlaying of 2D sketch drawings. The grid of DEM heights were divided into adjacent triangles and the normal at each vertex was calculated as the mean of the normals for adjoining triangles (Watt, 1989). OpenGL calculates the intensity of grey at each point within the triangles by linear interpolation of the intensities at the vertices of triangles. With Gouraud shading the boundaries of the triangles are not visible at high resolution. It is important to avoid artifacts in luminance-based edge-detection. The system supports orthographic and perspective projections. Figure 5 shows the main window of the sketching system, showing the tool bar and an orthographic projection of the Port Talbot DEM as a grey-scale map. This grey scale "colour" map is accessed using OpenGL. The system is used in "Nomal Mode" for the above stages.

When the user is in "Sketch Mode" the luminance map is recalculated each time the scene changes. The user can then experiment with selected edge detectors and their parameters. The radio buttons on the right of Figure 6 provide a choice of sketching operators. The parameters for each operator are grouped on the left. Feedback on the elapsed time, and the number and percentage of points retained in the sketch are provided in the lower part of the screen.

Figure 7: The luminance image of a part of the Port Talbot DEM

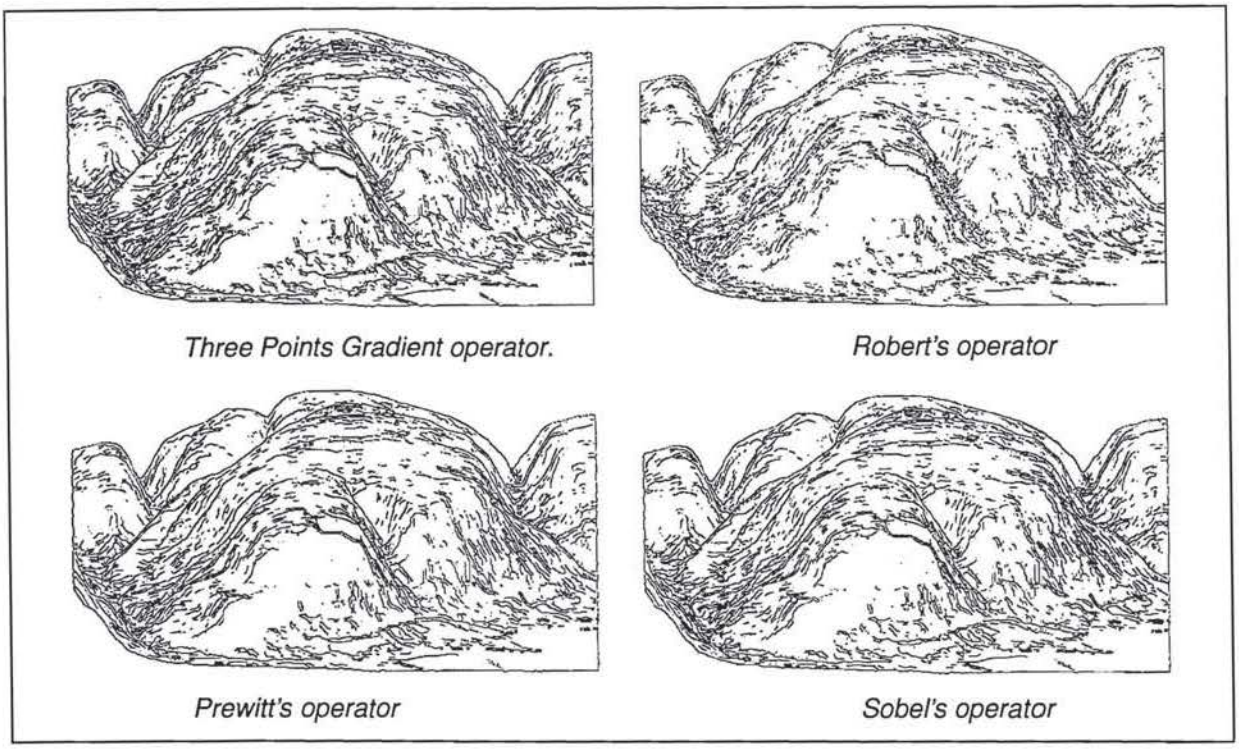


Figure 8: First derivative edge-detectors with non-maxima suppression
(*Original Image:* 600*600 pixels; *Threshold Value*: 350)

Method	Computation time (millisec)	Number of selected pixels	Percentage of selected pixels
3-points-gradient	2033	25963	8.9%
Robert	2073	16949	5.8%
Prewitt	2313	23710	8.1%
Sobel	2323	24512	8.4%

Table 1: Sketch statistics with non-maxima suppression

A 400 x 400 pixel image can be sketched at the rate of about two frames per second. A high resolution full screen image can take up to 5 seconds for some operators at present. The user can produce two different types of movies. In the orthographic mode, the movie is merely an animation of the terrain model. The control point consists of three rotation angles and of the translation vector, defining the position and orientation of the terrain model in the original reference. In perspective mode, the movie consists of a smooth movement of the camera in the 3D scene. In this mode, the control points in a trajectory correspond to the positions of the camera with their reference and vector speed, defining the local orientation and speed. The user chooses a set of control points for the key frames. The sketching program automatically generates the trajectory using Bezier curves and derives the in-between frames. The frames are converted into an MPEG movie using third-party software, such as PixelShrink (CeQuadrat, Online).

5. Comparison of some edge detectors for sketching

The project compared the output from the first and second order differential methods, as well as the more complex Canny operator. These image operators are described in Lesage (1999, Chapter 4) who includes references to web resources, such as Bock (1998), Owens (1997), Fisher et al (1996) and Ruzon (1999), and other primary sources, such as Canny (1986). Edges are usually detected as peaks in the first derivative or zero-crossings in the second derivative (Marr and Hildreth, 1980). Since the peaks are sensitive to noise, the images are smoothed using mean, median or Gaussian filtering. A sample of sketches, from Lesage's (1999) unpublished MSc thesis, is provided below to highlight the implications with respect to future work.

5.1 Some simple first derivative edge detectors

The input was the 600 x 600 luminance map shown in Figure 7. Figure 8 shows the result of filtering the magnitude of edges, as computed by the four named first derivative edge detectors, with non-maxima suppression perpendicular to the edges. Table 1 provides the statistics for these sketches. Even with less than 10% of input pixels, the sketches are very similar - they are noisy and cluttered and illegible in places. Even with less than 6% of pixels for the Robert's operator, there is a lack of clarity due to too much data in some places and too little in others. Some spurs and plateau edges are not clearly depicted. Figure 9 shows the impact of the resolution of the luminance map on the quality of the sketch obtained with the Sobel operator. However, all the first derivatives have a tendency to output double lines, which are not easy to eliminate without reference to the model.

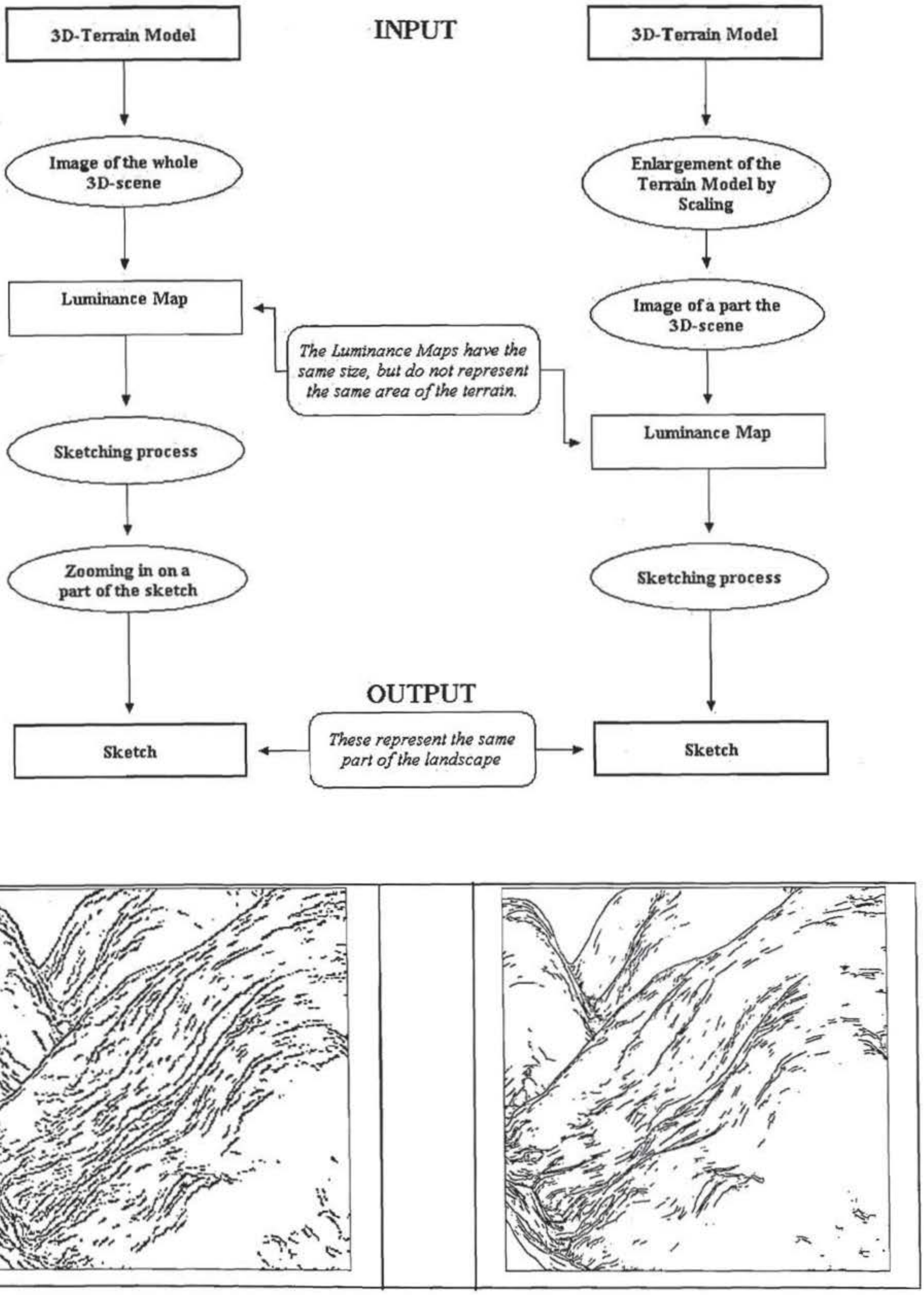
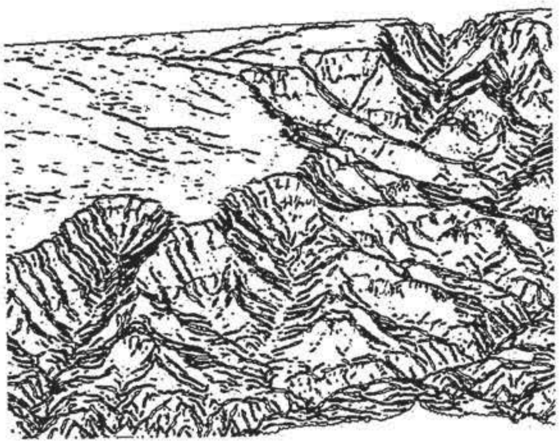
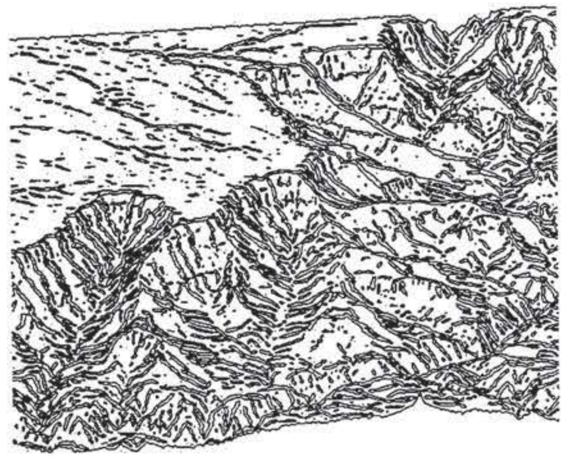


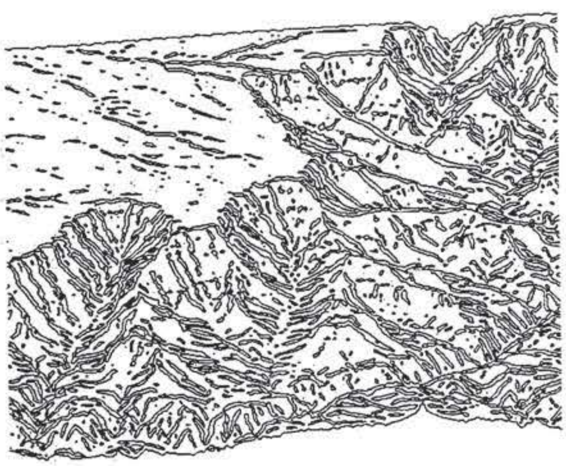
Figure 9: Comparison of zooming in before and after sketching



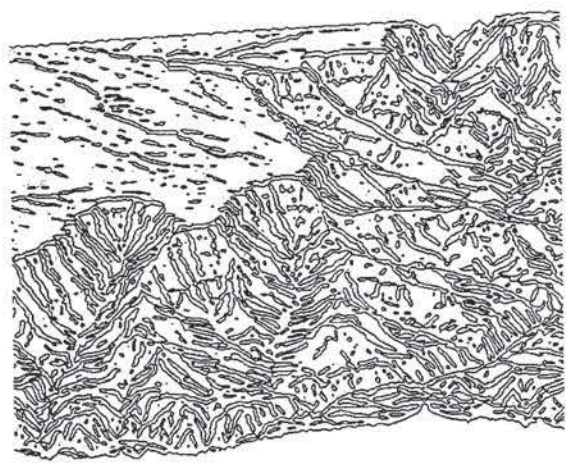
Marr 1: Gaussian(dim=5, σ=0.75)



Marr 2: Gaussian(dim=7, σ=1.03)



Marr 3: Gaussian(dim=9, σ=1.35)



Marr 4: Gaussian(dim=11, σ=1.60)

Figure 10: Some sketches derived by detection of zero-crossings

Dimension of the Gaussian mask	σ standard deviation	Computation time (millisec)	Number of selected pixels	Percentage of selected pixels
5	0.75	2223	53594	18.3
7	1.03	2774	50430	17.2
9	1.35	3465	41070	14.0
11	1.60	4357	42087	14.4

Table 2: Sketch statistics for the zero-crossings detector

5.2 Zero crossings of second derivatives

Unlike the first order derivatives which are directional, second derivatives are widely used because they are symmetric and can detect edges in all directions. It is also easier to localise zero-crossings of the second derivative than the maxima in the first. The primal sketches in Figure 10 were generated by increasing the width and the standard deviation of the convolution mask in Gaussian pre-smoothing as indicated in Table 2. All the figures have the closed contours typical of Marr's raw primal sketch. All creases and occluding contours tend to be picked out and increasing the Gaussian smoothing enlarges the loops, making the output worse, rather than better. The output is relatively worse than those obtained with the first derivative.

5.3 The Canny operator

The Canny operator is a more complex operator based on first derivatives (see Fisher et al, 1996; Ruzon, 1999). Edges are assumed to be perpendicular to the maximum gradient. We found that pre-smoothing with two-dimensional Gaussian masks varying in width and standard deviation (see Figure 11) gave a more generalised and less cluttered sketch (see Lesage, 1999). The edge points were filtered by non-maxima suppression and connected into edges. Insignificant edges were eliminated using Canny's idea of "thresholding histeresy", which is controlled by the two parameters shown in Figure 6, namely h2 which determines edge selection, and h1 which serves to limit edge extension. Lesage (1999) investigated the effect of varying h1, h2 and pre-smoothing on the Crater Lake DEM (Figure 12). These parameters have a significant impact on the resulting sketch. Figure 13 shows the impact of varying just h1, on a pre-smoothed image, to achieve full and no extension respectively (see highlighted areas). While these sketches of Crater Lake are very impressive, the best sketch of Port Talbot (see Figure 14) was not as successful. All the occluding contours are detected. Some other prominent creases are also picked out. However, there is cluttered and confusing detail in the valley bottom, while important breaks of slope are not detected since they are not sharp.

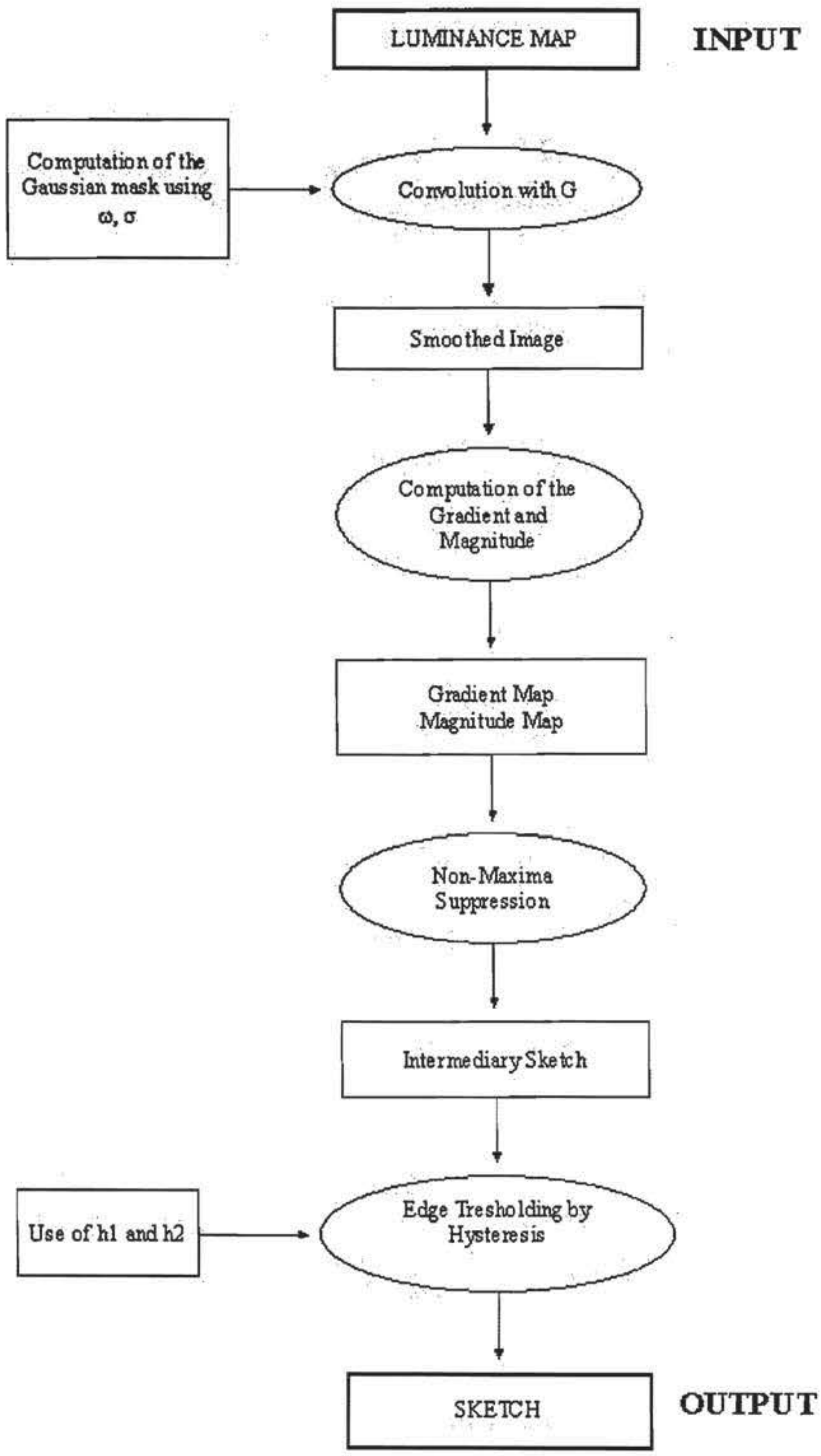


Figure 11: Canny edge detector pipeline

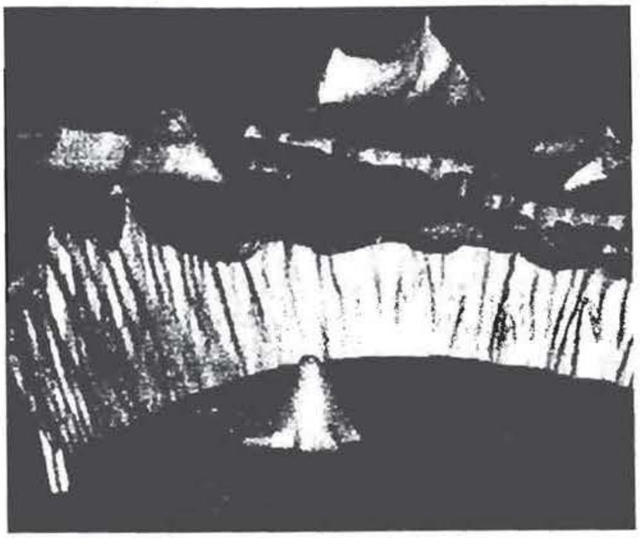


Figure 12: A luminance image of crater DEM

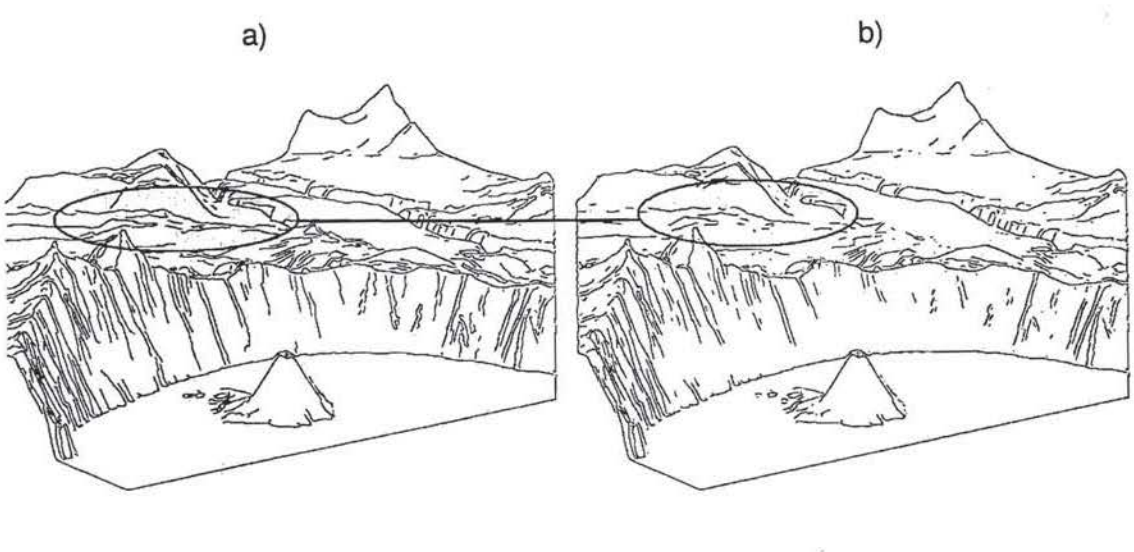


Figure 13: Sketching with Canny operator: impact of the lower threshold value
a) h2=0.05, h1=0 (full extension); b) h2=h1=0.05 (no extension)

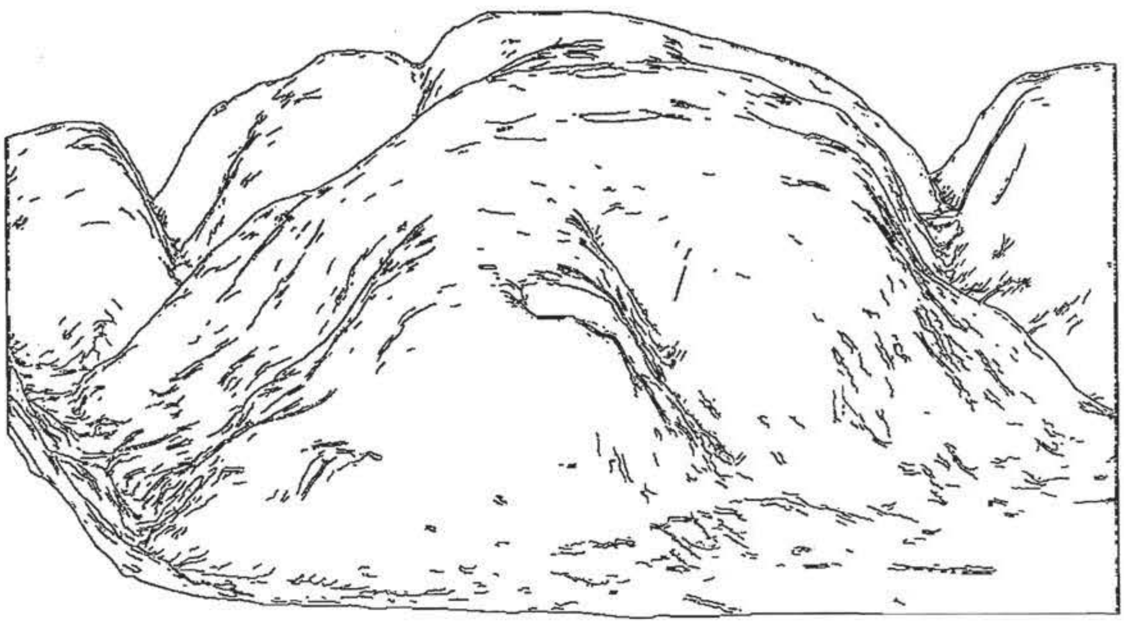


Figure 14: Black and white sketch with Canny Operator (h1=0.07 and h2=0.5*h1)

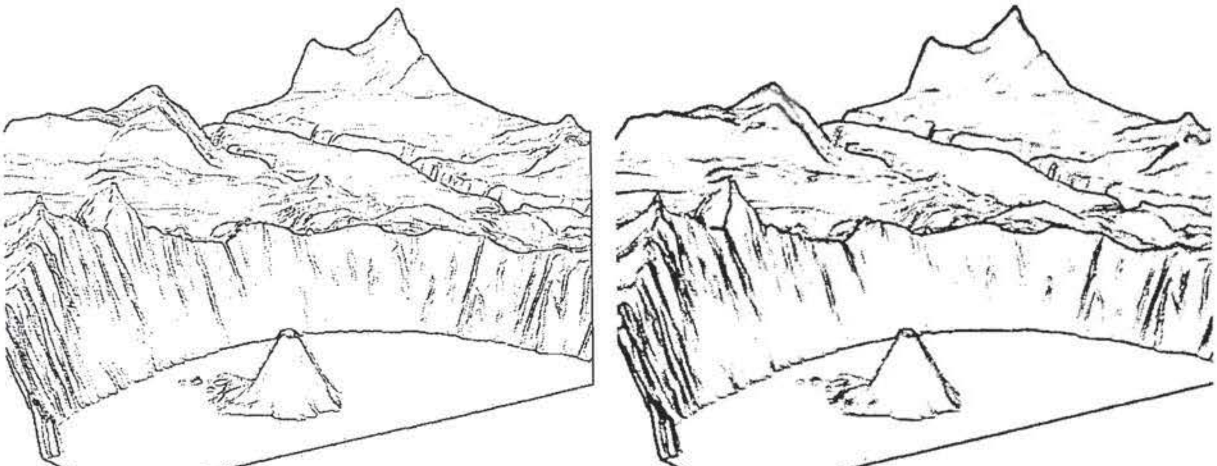


Figure 15: Pencil and charcoal sketches with Canny Operator

6. Styles of sketching

Figures 13 and 15 show how the output of the Canny operator may be varied to produce black and white "pen and ink"; 256-level grey-scale "pencil" sketches; and, a "charcoal" effect by varying the line thickness. While these sketches of the Crater Lake are impressive, the more eroded slopes of the Pennant plateau in the Port Talbot DEM show up the limitations of using the single headlight. Both the grey-scale sketch obtained with the Canny operator and the charcoal sketch derived using the Sobel operator without non-maxima suppression are very similar with respect to the edges detected and emphasised (Figures 16 and 17). The output of double lines have already been noted and the use of line thickness and grey-scale reduce their visual impact as well as that of noise. The sketches give a good impression of the overall form. However, they are misleading and incomplete. Weighting the lines on edge strength can connect spatially disjoint contours into inappropriate occluding contours. For example, compare contour A in Figure 16 with the corresponding contour in the P-stroke sketch. The grey-scale sketch connects the bottom half of the spur in front with the top part of a shoulder further back. This is topologically incorrect. Also, the variations in symbolism do not pick out the wavecut platform at B as well as the P-stoke sketch does. The spurs at C and D are not clearly defined. The missing plateau edge, for example at E, combined with the detection of backfacing slopes gives the misleading impression that the edge is located much further back on the latter. Such generalisation distorts reality. Other missing information is largely due to the use of the single headlight. Even some of the edges of the Crater rim, which form distinct internal creases, are not emphasised (figures 13 and 15).

7. Sketches based on two lights and animations

The project investigated whether some missing edges could be detected by using two orthogonal lights to produce two separate sketches, which were then combined. Figure 18 shows that the sketches pick out different features of the terrain. The river valley is much clearer in the sketch with vertical lighting, partly because it excludes the detail in the valley. Whilst effective, the combined sketch includes too much detail, even ignoring double lines, for use as a background map. A higher tolerance will lead to an absence of cues on the plateau top; this will give an impression of a planed surface as in the sketch with the vertical light in Figure 18.

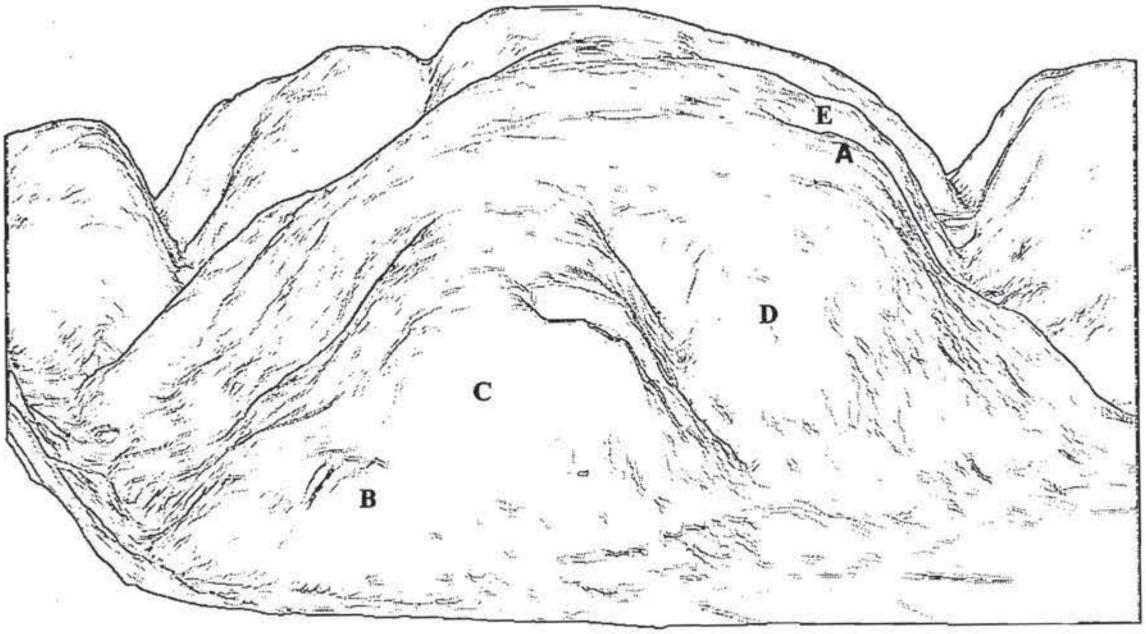


Figure 16: Grey-scale pencil sketch with Canny operator

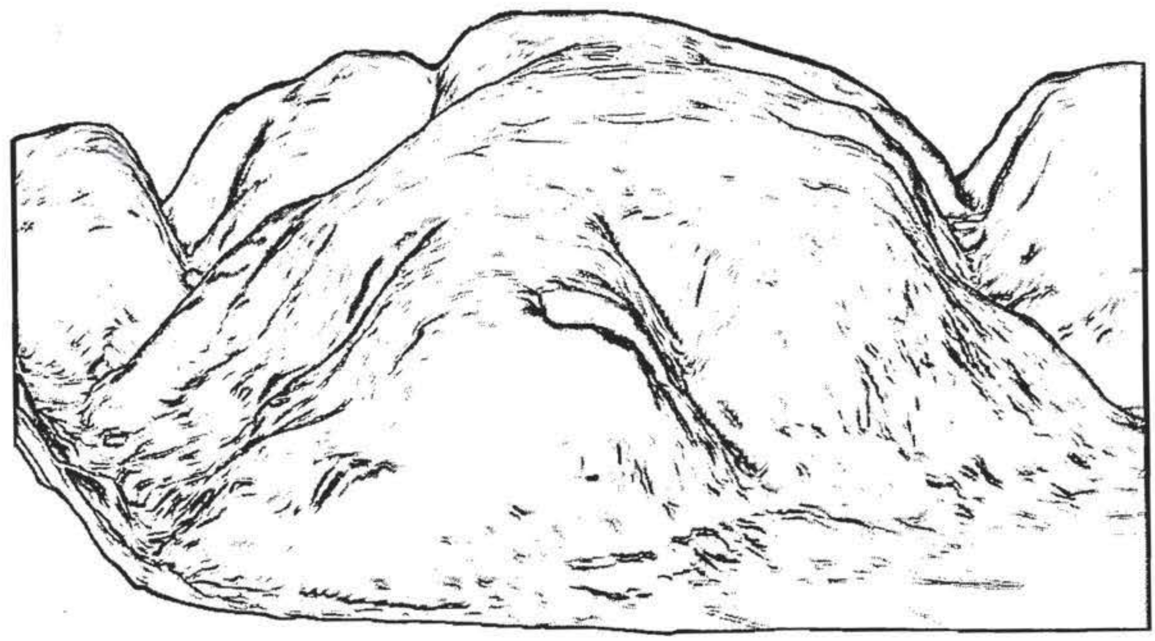
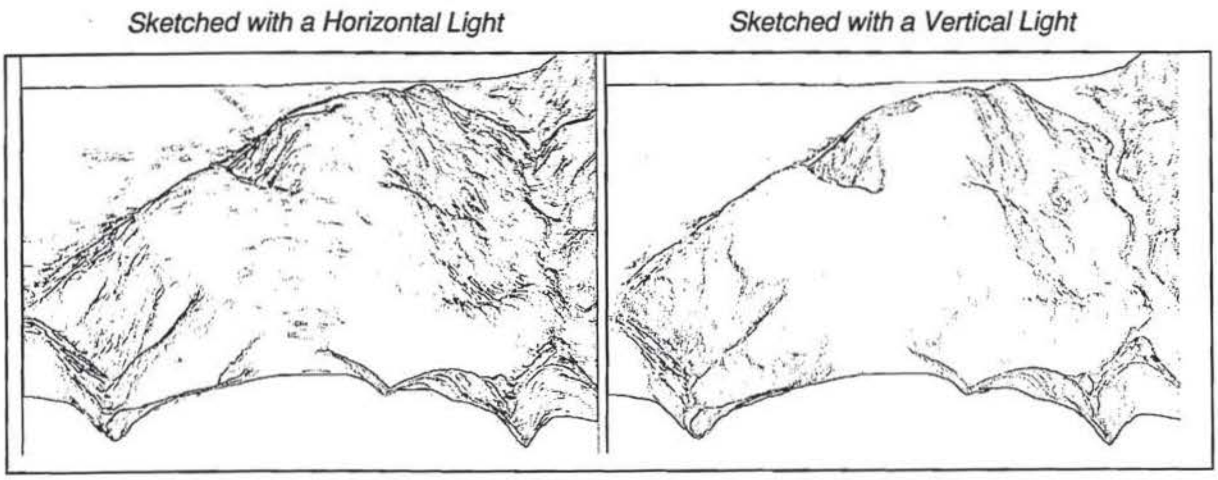
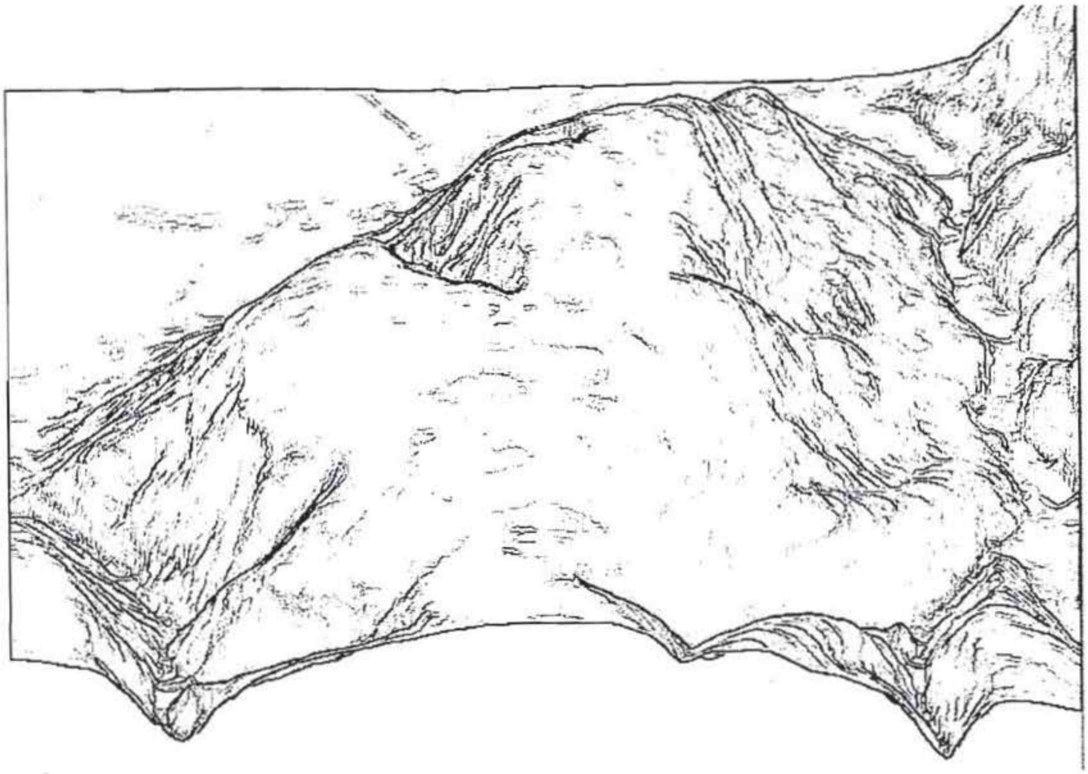


Figure 17: A Sobel sketch using grey levels and different thickness strokes





Result of adding the two sketches above

Figure 18: Superimposition of two sketches with vertical and horizontal lighting

The combination of the two lights conveyed the 3D form of the terrain much more effectively. Since successive frames are mentally integrated into a 3D form in animations, it is possible to exclude more detail in movies. Animations of two-light based sketches may be found at:
http://www2.dcs.hull.ac.uk/CISRG/people/lesage/Port%20Talbot.mpg
http://www2.dcs.hull.ac.uk/CISRG/projects/Royal-Inst/lesage/Crater_2Lights.mpg

The lighter grey-scale values, lost on conversion to mpeg, result in noticeable loss in the sharpness and clarity of the original sketches with about 10% of non-white pixels. These sketch animations facilitate the perception of the solid 3D mass of terrain. No part of the sketch is seen as detached from the surface. When this work was first demonstrated on the occasion of Lord Puttnam's lecture on "Where Art Meets Science" (Visvalingam, 1999a), the reaction of some artists to the movies showed that people react to sketches according to their own inclinations. Some peoples' body movement showed that they were responding to the graceful motion of the ghostly terrain, and that they were not paying attention to surface detail. This is similar to people moving with the rhythm of music even when they were not paying attention to the lyric. They saw immense potential for use of sketches in the development of dynamic 3D art forms.

If we move from the aesthetic experience to scientific usage, many of the limitations of luminance-based sketching (see Figure 16) become less of a problem in animated sketches. With varying views, merged occluding contours separate out to give a clearer impression of the terrain; missing edges and spurs can be mentally interpolated; and, the wavecut platform becomes prominent. The interactive sketching system enables users to vary the camera position and tolerance levels to study the landform in some detail. However on excessive zoom, saw-toothed edges appear, for example on the Crater rim, revealing the underlying triangulated model. Nevertheless, the system could be useful to specialists in the earth sciences, especially geomorphologists and geologists. Sketches are indispensable in textbooks in these fields and there is scope for including mpeg videos and Java applets in the ever-growing web-based learning resources. However, there is still a need to improve the quality of the sketch in each frame a) to guide the perception of users who are not landform specialists, and b) for use as stand-alone illustrations.

8. Discussion and conclusion

Sketching, like visualization, serves multiple purposes. Only two contrasting applications are considered here, namely artistic and scientific. The animated sketches were aesthetically appealing to those engaged in the visual arts, who saw immense potential for the development of new dynamic art forms. Whereas the second author was concerned about the absence of some of the creases depicted in P-stroke sketches, others felt that the suggestive and incomplete nature of the movies was much more appealing to the imagination and was its main attraction. Clearly, the same techniques may be applied to other surfaces and solid objects, including torsos as already indicated by Northrup and Markosian (2000).

There is ample scope for sketch-based browsing of terrain data on remote sources. However, as in photorealism, static images need to be more informative than fleeting animated images. This is particularly important for scientific use of sketches in the earth sciences. Cartographic maps are knowledge-based interpretations of data gained from multiple viewpoints - they are constructions and not passive perceptions.

Seeing is highly subjective; it is well known that the detection of some logical inconsistencies is dependent on priming and all earth scientists are trained in map reading, analysis and interpretation. So, not everyone would note the problems identified earlier or regard them as significant. This is one reason why there is continuing dissatisfaction with visual evaluations of cartographic algorithms. Equally, as Visvalingam and Whyatt (1990) demonstrated, existing mathematical measures (often based on goodness of fit) are only appropriate for rating the approximation of lines and surfaces – not for sketching. Cartographic maps can be topological (such as London Underground maps) but even so the sketch elements must be logically connected. Visvalingam and Dowson (2000) suggested the scope for basing such evaluations on cognitive criteria. Even if it is difficult to automate such cognitive evaluations, they provide a basis for conducting visual evaluations on logical arguments rather than gut feelings. Such logical arguments were presented to justify the investigation of luminance maps as input for sketching and later to evaluate this approach.

To recapitulate, the main approach within the CISRG is model-based. There were two main stages in P-stroke sketching. There is an initial view independent process which identifies the important of breaks of slope. The P-stroke depiction of this information is view-dependent and it provided a quick means of evaluating whether the breaks of slope were being identified correctly. The sketches showed that Visvalingam's line filtering algorithm was better than the Ramer/Douglas-Peucker algorithm. Sketches based on object forms will be incomplete without complementary view dependent cues, such as silhouettes or occluding contours. This can be abstracted from both z-buffers and luminance maps. If occluding contours are defined as the locus of points marking discontinuities in depth along the line of sight, as in the z-buffer approach, they are not sufficient on their own for indicating the outline of convex landforms which provide the most important cues of relative depth in pictures. Also, occluding contours alone can form an incoherent sketch and convex forms may seem to float. The luminance image based approach was investigated since it has the capacity to pick out more relevant cues as suggested by Watt (1988). However, a number of problems were identified in this paper. Also, a single horizontal front light is not sufficient to detect some of the perceived breaks of slope even on dramatic landscapes, such as Crater Lake. Also, most terrain is undulating with no distinct internal creases. The addition of sketches, from top lit luminance maps, locates some of these edges correctly. However, edges in luminance images can mislead and a hybrid approach may be needed for chaining and depicting even the basic cues, such as silhouettes (see Northrup and Markosian, 2000). This may enable correct chaining and depiction of occluding contours and other creases. However, there is still the age-old problem of a lack of balance tied to use of global filter. Equally, the results from the Canny operator required the tweaking of several parameters for each terrain.

Despite the problems, it would be interesting to push the limits of data-driven sketching. More recent edge detectors (the Mirage operator by Watt and Morgan (1985) and, especially the detection of phase congruence by Burr and Morrone (1990) could be investigated. Equally, there is merit in investigating pure 3D model-based approaches, from a view centred perspective. This could be used to complement and to cull the current view independent filtering of DEM cells, portrayed in the P-stroke sketch. There is a need to investigate other styles of vector depiction of surfaces, such as terrain, where there are no distinct breaks of slope. Even in photographs, let alone painted landscapes, topographic information do not always bond well with the terrain surface. It would be interesting to investigate the problems which emerge when such information are included in minimalist sketches.

As noted earlier, even the conceptually well-defined silhouette is a continuing challenge for researchers. We are therefore still a long way from automating the ill-defined art of generalisation, which guides landscape sketching. There were relatively few masters of the art. This strand of research within the CISRG was inspired by their art and is dedicated to them.

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