Non-invasive three-dimensional recording of Aboriginal rock art using cost-effective digital photogrammetry

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NON-INVASIVE THREE-DIMENSIONAL RECORDING OF ABORIGINAL ROCK ART USING COST-EFFECTIVE DIGITAL PHOTOGRAMMETRY

J. H. Chandler, J. G. Fryer and H. T. Kniest

Abstract. Inexpensive digital cameras combined with appropriate and accessible photogrammetric software are now capable of generating accurate and dense three-dimensional records of rock art using automated methods. This paper describes the development of a system of recording rock art that is portable, inexpensive, non-invasive and does not require extensive photogrammetric expertise. The effectiveness of the approach is demonstrated for two petroglyphs in New South Wales, Australia; results are presented and accuracies assessed.

Introduction

Recording is the essential prerequisite for any database compiled for researching into, and conservation of, rock art (Simpson et al. 2004). Recording rock art has been achieved using a variety of methods in the past, including photogrammetry, but recent developments in digital photogrammetry provide new opportunities for three-dimensional data capture and processing. The purpose of this paper is to demonstrate that:

- Inexpensive digital cameras can be used to acquire imagery suitable for photogrammetric measurement and recording of rock art;
- Field equipment can be restricted to just a digital camera and a single three-metre pocket tape, ideally suited to conducting fieldwork where transport is restricted to foot;
- Simple and non-invasive imaging and control configurations can be adopted that allow non-photogrammetrists to capture appropriate imagery in minutes;
- Modern software that is now widely available is able to extract spatial data in three-dimensions in the form of digital elevation models (DEMs) and orthophotographs. If appropriate camera calibration routines are adopted then such data can be highly accurate, typically at sub-millimetre level;
- Data is recorded in three dimensions and rectifying imagery to an arbitrary plane is no longer required;
- Photogrammetric data can be used to answer a variety of research questions and be used to create accurate 3D representations and fly-through displays.

This paper identifies the methods currently used for recording rock art before reviewing previous applications of photogrammetry to the field. A simple and non-invasive photogrammetric recording method is presented, which uses an inexpensive digital camera to extract dense morphological and spectral data to record the rock art in intricate detail. The method was tested at two petroglyph sites in Australia and results are presented. The accuracy of the derived data is assessed and the benefit of the approach compared with other recording studies recently published in the rock art literature. Although the case studies described in this paper focus upon petroglyphs, readers should be aware that the recording methodology has been used successfully by the authors at two pictogram sites: the Baiame Cave, near Broke, and Swinton's Cave, near Gosford; both sites are located in New South Wales, Australia.

Recording of rock art

Current methods and limitations

The creation of some form of facsimile of existing rock art is clearly desirable, allowing further scientific study, detailed non-contact measurement and, via archiving, partial protection against loss in the event of destruction. The desirability to create such 'recordings' of petroglyphs was recognised many years ago, and indeed W. D. Campbell began to record petroglyphs in the wider Sydney area of Australia in 1899 (Stanbury and Clegg 1990). There are three main methods of recording rock art currently in use today: drawing, tracing and photography (Stanbury and Clegg 1990). Although of increasing sophistication, all suffer from various limitations. Free-hand drawing or sketching is simple and easy to conduct in the field but provides only a two-dimensional record and is generally inaccurate (Brayer et al. 1998). Direct rubbing using paper or tracing using plastic sheets is commonly adopted but the method creates large volumes of media, which have to be photographically reduced for more efficient storage. It is also invasive, requiring the physical touching of the art and requires extensive field time (P. Taçon, pers. comm.

Dec. 2004). The placing of a grid over the object and transferring detail one square at a time solves the physical reduction problem directly, but again requires time and patience in the field and inaccuracies are inevitably introduced. The use of photography remains universal, particularly for simple recording and qualitative use, but the extraction of quantitative data using imagery is less common. Donnan (1999) identifies the potential of digital image processing (DIP) for recording rock art in Northumberland, U.K., and Clogg et al. (2000) provide a review. In their U.K.-based study, a digital filter and simple thresholding methods are used to identify pictograms from the surrounding rock surface using spectral information alone (Clogg et al. 2000). In Australia, David et al. (2003) and Brady et al. (2004) cite how simple manipulation of saturation and contrast of digital imagery representing pictograms located in Dauan (near Papua New Guinea) and Mua Islands revealed 'previously invisible motifs'.

The idea of recording rock art in *three* spatial dimensions is not new and indeed sophisticated optical methods to derive surface topography have been developed (e.g. Bertani et al. 1995, 1997). Although highly accurate, such systems are expensive and not practicable for fieldwork or for recording large objects typically found in the field. Laser scanning is one technology that has demonstrated potential for rock art recording (Boehler et al. 2001; Trinks et al. 2005; Goskar et al. 2003), particularly when combined with imaging. El-Hakim et al. (2004) merged spatial data derived using a laser scanner with spectral data obtained using an inexpensive digital camera to generate a virtual model of an Aboriginal pictogram site in N.S.W., Australia. The merging of image and spatial data proved time consuming, although the latest generation of scanners, which include an inbuilt imaging sensor, should resolve this problem. However, all current laser scanners remain bulky, expensive and require some expertise to operate. Ogleby (2004) predicts the future development of the 'Ridjidigital', a combined terra-pixel imaging and laser-scanning device with limitless storage. There is a demonstrable need for equipment and methodology to record rock art in an efficient manner as urban sprawl, widening of arterial roads, vandalism and the accumulating effects of environmental pollution increase the deterioration rate of petroglyphs (P. Taçon, pers. comm. 2004). Despite the valued contributions of other researchers, the authors believe there remains an urgent need for equipment and a methodology to record rock art in three dimensions cheaply, easily and without expert personnel in the field. A solution based upon photogrammetry has suggested potential for many years.

Past use of photogrammetry for archaeological and rock art recording

One of the earliest examples of photogrammetry being used to record rock surfaces was conducted by Atkinson (1968) at Stonehenge in the U.K. A special stereo-metric camera system was used to record a small petroglyph from which contours were manually measured using a specialised 'Thomson Watts' plotting machine. Scogings (1978) used a similar method to record petroglyphs at Kinderdam, 300 km west of Johannesburg, South Africa. Features were again represented using contours, generated manually at 1 mm intervals on a 1:1 scale plot. In a series of related projects, Rivett (1979) and Ogleby and Rivett (1985) demonstrated the benefits of photogrammetry for recording rock art, both petroglyphs and pictograms. Fieldwork was conducted at a series of sites around Australia, including Kakadu National Park, Northern Territory; Whale Cave, N.S.W.; Quinkan, Queensland; Hawkesbury, N.S.W.; and various sites in Western Australia. Their *Handbook of photogrammetry* (Ogleby and Rivett 1985) was a key text, at that time, describing how to conduct a photogrammetric survey for field archaeology. More recently, Ogleby (1995; 1999; 2000) has continued to demonstrate the benefits of photogrammetry to a wider archaeological audience, including of the Ayutthaya temple in Thailand (Ogleby 1999) and Mount Olympus in Greece (Ogleby 2000). In these two examples, an important final product has been the virtual model, enabling the visualisation of the site from any perspective. A similar virtual model was generated by Simpson et al. (2004) who describe the use of the *photomodeler* (*www.photomodeler.com*) software package to create 3D models of incised rock art in Northumberland, U.K. Unfortunately, their approach requires the painstaking sticking of self-adhesive targets over the entire surface area of the rock and the precise positioning of their digital sensor. Subsequent measurement is also manual and consequently time consuming. The *photomodeler* package is also widely adopted in the developing field of *Archaeological GIS*, where it is being increasingly utilised to create Virtual Reality models, for example of Hepburn Castle (Gillings and Goodrick 1996), and assisting archaeological problems that have a spatial component.

Limitations with traditional photogrammetry

The principal reason why photogrammetry has not been more widely adopted in the past has been the financial cost, particularly the equipment and skilled labour necessary (Rosenfeld 1988). Specialised metric cameras costing in excess of 10 000 US dollars were required, which needed to be calibrated to enable accurate data to be derived. Traditional instrumentation also enforced strict geometric constraints upon imagery that could be used and required conventional two-dimensional film-based maps to be produced. All derived spatial data had to be measured manually and plotted to an average or mean plane, introducing artificial scale distortions into the plotted data (Ogleby and Rivett 1985). This paper demonstrates that PC-based computing power combined with automated modern photogrammetric software can overcome most of these traditional difficulties.

The International Committee for Architectural Photogrammetry (CIPA) was established to improve the recording of cultural monuments using photogrammetry and related methods. One of its important recommendations is the '3 × 3' principle (Herbig and Waldhausl 1997), which promotes the acquisition of photography suitable for photogrammetric measurement. The principles include three geometrical rules (control, base/distance ratio, normal photography); three photographic rules (constant camera geometry, soft illumination, film type); and three organisational rules (sketches, care, checks). It is disappointing that these principles and photogrammetric methods are not more widely adopted. Indeed, one of the tasks identified by CIPA is to '*bridge the gap*' (Letellier 2001) between the information user and the information provider. In rock art recording, Palumbo and Ogleby (2004) note that the impediment preventing wider adoption of photogrammetry is the lack of inexpensive, portable, automated and easy to use systems. It is believed that the photogrammetric methods described in this paper will provide a significant step towards achieving that objective.

Figure 1. *Image capture.*

Project work

Previous research conducted by the authors had demonstrated that consumer-grade digital cameras could be used to produce accurate surface measurements (Chandler et al. 2005). In that study, a range of inexpensive digital cameras was compared to an expensive digital sensor (Kodak DCS460) that had proven metric capability (Fraser and Shortis 1995). It was determined that surface accuracies of 0.4 mm could be obtained using the inexpensive digital cameras located at a distance of one metre; these accuracies being appropriate for the measurement of surfaces necessary to support a wide range of scientific work, including on the human body and in quantifying river channel change (Chandler et al. 2005).

One additional area that seemed to be a potential beneficiary was in the recording of rock art, particularly where sites are located in inaccessible areas. Discussions with rock art specialists (P. Taçon, pers. comm. Dec. 2004; C. Ogleby, pers. comm. Nov. 2004) and a wider examination of rock art literature reinforced the perceived need to develop cost-effective methods of recording rock art in three dimensions, particularly using equipment that can be easily carried in the field. Furthermore, additional benefits would accrue if the recording phase could be conducted by those with the relevant rock art expertise and without extensive photogrammetric training. It was recognised also that simple techniques based upon accessible software are essential if current rock art recorders are to embrace any new approach. If successful, it was believed that appropriate developments could provide rock art conservators with an additional tool to record rock art sites.

Field sites

A series of field sites were identified in Yengo National Park, New South Wales, Australia. These were typical of the 'Sydney' style (Stanbury and Clegg 1990) petroglyphs, being engraved on horizontal sandstone outcrops in the area north and to the west of Sydney, Australia. These rock carvings have undergone stylistic change over many thousands of years (Stanbury and Clegg 1990) as Aboriginal groups have carved pictures on prominent sandstone slabs at a limited number of ceremonial sites. These petroglyphs are only partly understood and recording is crucial before they disappear forever, victims of natural erosion and vandalism. Data was captured at two distinct field sites, the first resembled one of Australia's megafauna animals, the *Zygomaturus trilobus*, so named because of the three 'bumps' on its head. For convenience, this petroglyph is referred to as 'Zygo' here, and is approximately 2 m in length. The second is slightly smaller (1.4 m), a representation similar to a human figure and has been variously referred to as 'Big Fella', according to a local Aboriginal custodian (Gordon, pers. comm., Sept. 2001). Both petroglyphs are located in the Yengo National Park, in the region of 33ºS, 151ºE.

Data capture

Imagery was acquired for both sites using a 3 mega-pixel Nikon CoolPix 3100 digital camera costing just US$400 and a 6 mega-pixel Kodak DCS460. Originally, the Kodak DCS460 cost US$30 000 (1997), although the Kodak DCS Pro 14n, which is perhaps the current equivalent of the older DCS460, retails for US$4000 (Dec. 2004). Both cameras were handheld during use and elevated above the rock surface using a portable and lightweight 1.2-metre aluminium stepladder (Fig. 1). The Nikon camera is equipped with a variable focus lens and the widest angle setting was adopted to optimise coverage. Camera height was then adjusted until the full viewing format was filled by the petroglyph. The smaller Big Fella site was captured with the camera at a height of 1.4 m, the larger Zygo requiring an elevation of 1.6 m. Two overlapping images were obtained of the petroglyph by displacing the camera horizontally 15–25 cm between the two images, so providing a single 'stereo-pair' that can be viewed stereoscopically (Wolf 2001). The exact position of the camera is not critical, provided the base/distance ratio is between acceptable limits (1:5 to 1:10). This contrasts greatly to image acquisition required by photogrammetry in the past (Ogleby and Rivett 1985) where strict positioning was dictated by the geometric limits imposed by traditional plotting instruments.

Although it is possible to measure and extract data using just a single pair of photographs it is often valuable to place some form of 'control' within the object space. This control allows the extracted data to be more useful and enables more complex objects to be recorded using multiple image pairs. Control can be of two forms. The simplest is to utilise a scale bar, which allows final data to be extracted to a known scale. Furthermore, if the scale bar can be placed horizontally it is generally possible to extract data within a co-ordinate system that is approximately related to the local vertical. The Zygo test was conducted using just one scale bar, a survey staff, which was laid on the ground towards the periphery of the engraved Zygo (Fig. 2).

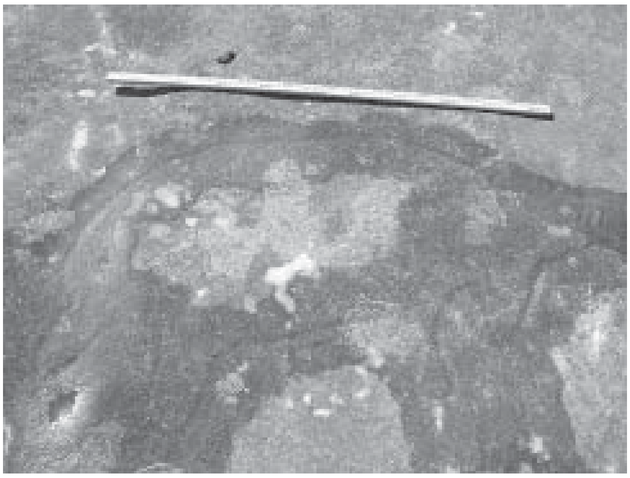

Figure 2. *Zygo site, survey staff used as simple scale bar control.*

If the object is too large to be captured using a single stereo-pair, or extracted data needs to be oriented exactly to the local vertical or other reference datum, then a series of targets should be placed around the feature. A minimum of six is recommended and although a variety of target designs can be adopted, manufactured targets made of plastic are cost-effective. Targets can be stuck temporarily to the rocks surface using silicone bathroom sealant and then removed easily after the photographs have been acquired. The three-dimensional co-ordinates of each target need to be determined using conventional field survey methods. Either a theodolite intersection method can be used or if a modern Total Station equipped with the reflector-less EDM is available, then a direct bearing and distance approach can be efficient. Simple taping between targets and height differences measured using a builder's level can also be used to determine the location of the control points, when site conditions permit. The Big Fella site was controlled using a series of eight targeted points (Fig. 3); their co-ordinates were determined using a Leica series 1100 Total

Figure 3. *Big Fella site, targeted control.*

Figure 4. *Total Station used for co-ordinating control and generating check data.*

Station with reflector-less EDM (Fig. 4). In this case, the Total Station was used also to measure a further set of co-ordinates to allow the accuracy of photogrammetrically acquired data to be quantified. The Total Station was motorised and a computer program had been developed to drive the telescope to point in a set of predefined directions. For each direction, the reflector-less EDM was able to measure the distance to the rock, so generating a set of *xyz* co-ordinates representing the actual rock surface.

Data capture was achieved very rapidly, particularly for the Zygo site where all recording was completed in less than 25 minutes. This included photo acquisition using the two cameras used for these tests. Data capture for the Big Fella took approximately 40 minutes, comprised of 10 minutes for image acquisition and 30 minutes for targeting and co-ordination using the Total Station. A further one hour was required to measure additional 'check data' necessary to assess the accuracy of the photogrammetric dataset (Fig. 4). All equipment was carried by two field workers and included: an aluminium stepladder, a Total Station, the cameras and a notebook. For simple objects (Fig. 2) the Total Station could be replaced by a pocket tape.

Photogrammetric data processing — Nikon Coolpix

Data processing consists of standard photogrammetric procedures that involve analysing the imagery acquired, extracting digital elevation models (DEMs) and creating orthophotographs (Leica Geosystems 2003). The latter appear similar to the original imagery but distortions in the image arising from varying topographic surface (relief distortion) and non-vertical camera position (tilt distortion) are removed so that the final orthophotograph has the metric qualities of a map. All modern PCs are capable of performing the required operations and so expensive hardware is not necessary. Specialised software is required and some basic understanding of photogrammetric principles needs to be learnt before the data acquisition phase is likely to be successful. The software used for this project was the Leica Photogrammetry System (LPS) version 8.7 and a full commercial license costs approximately US$16 000 (Dec. 2004).

For the two case studies, imagery obtained using the Nikon Coolpix was downloaded using the standard PC interface provided by the camera supplier. Images were stored in JPEG format at a ratio of 1:2 compression; a high quality storage setting that avoids the loss of significant image information. The images were loaded into LPS and 'pyramid layers' created (Leica Geosystems 2003). These pyramid layers represent the original image at a range of lower resolutions and allow more efficient image viewing and manipulation. Unlike traditional photogrammetric processing, there is no requirement to carry out measurement for the inner orientation (IO). The digital CCD array that captured the original image is dimensionally stable and comparatively flat, so that it is only necessary to define the physical dimensions of each pixel. This is best achieved by knowing the physical size of the sensor and dividing these two dimensions by the sensor resolution (see inset). These data are provided in the camera specifications but Internet sources can be useful also (Dpreview 2004). Once the pixel sizes have been defined, it is possible to establish the position and orientation of each photograph at the instant the image was acquired, which is known as the exterior orientation (EO). This is achieved by measuring the image positions of the control points (points located either on the scaling device or physical targets). A minimum of six points is required, although eight are recommended, with points ideally distributed around the whole of the overlap area. Some experience is required when running the program to establish the EO. Appropriate weights need to be assigned to control co-ordinates and the results generated need to be assessed critically before acceptance. If a scaling bar is the sole source of control, then appropriate 'initial values' need to be entered for the positions and orientations of the photographs too. Finally, some form of camera calibration (Chandler et al. 2005) is required if accurate data are to be generated. There are three options, of increasing complexity and accuracy:

The Nikon Coolpix 3100

Physical size of sensor: 5.27 x 3.96 mm
Resolution of sensor: 2048 x 1536 pixels

Pixel in X = 5.27/2048 = 2.573 µm
Pixel in Y = 3.96/1536 = 2.576 µm

- Ignore camera calibration — low accuracy results, not recommended;
- Specify approximate focal length and utilise an approximate lens distortion model — appropriate for medium accuracy results;
- Carry out a process known by photogrammetrists as 'in-situ self-calibration'. This calibration determines the focal length of the camera at the time of the photography and any corrections needed because of distortions in the lens. This procedure can be achieved using either the self-calibrating capabilities of LPS or an external self-calibrating bundle adjustment. The procedure is essential for accurate data extraction.

For the Zygo site, where the survey staff provided the sole source of control (Fig. 2), two points on the staff were measured and combined with four extra features distributed over the overlap area. The distance between the two staff points was known and this allowed definition of a local and scaled co-ordinate system. Approximately fifty additional natural feature points were measured automatically and without user intervention using the LPS 'tie point' facility (Leica Geosystems 2003). All measurements were then downloaded and used in an external self-calibrating bundle adjustment to establish the critical geometric characteristics of the camera. These values were re-entered into the software, EO re-estimated and accepted. In future releases of the LPS software it is expected that appropriate self-calibrating capabilities will bypass the need to use an external program (Chandler et al. 2005).

A more simplified procedure was feasible for the Big Fella site, since co-ordinated control points had been installed. The targeted points were measured from which LPS was able to generate initial EO parameters. The 'tie point' facility was again used to generate a further fifty image points before an external self-calibrating bundle was used to establish inner camera geometry. These data were entered and a final restitution computed and accepted.

Results

DEM generation and subsequent data processing

Once acceptable exterior orientation parameters had been determined, it was possible to use the automated DEM generation tool to extract a dense matrix of point elevations to represent the morphology of the rock surface. The automated DEM generation tool uses an 'hierarchical feature point matching' algorithm (Leica Geosystems 2003). The algorithm relies on the identification of unique localised texture in the imagery and it has been suggested that natural and weathered rock surfaces create appropriate image texture for the algorithm to work effectively (Stojic et al. 1998; Chandler et al. 2001). Thousands of small features are identified on both images, their co-ordinates determined automatically and a regular grid of elevations generated through an interpolation process. The density of points in the final DEM is user-definable but grid spacing must not be smaller than five times the ground pixel resolution. The final resolution of the DEM is therefore dependent upon the scale of the imagery and the resolution of the original sensor. For the Big Fella site, it was possible to measure a DEM at 5 mm resolution, for the larger Zygo site an 8 mm DEM was obtained using the Nikon Coolpix imagery.

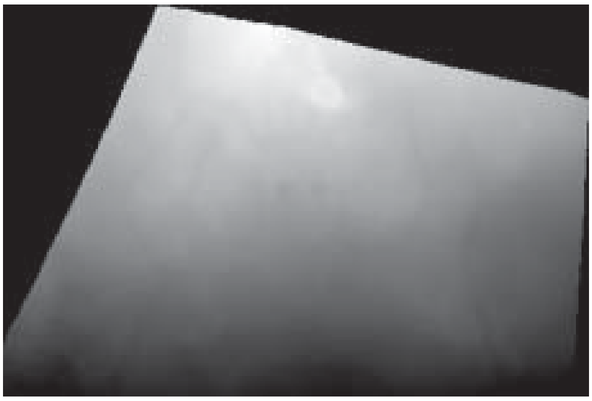

Figure 5. *DEM of Big Fella (5 mm resolution).*

Figure 5 is a greyscale representation of the Big Fella DEM in which white pixels indicate a higher absolute elevation than black pixels. It is encouraging that the engraved features of the petroglyph are just visible, particularly the two 'eyes' which, being 7–9 mm deep, provide a useful location indicator. However, the remaining engraved features are indistinct and initiatives to accentuate the engraved features using morphology alone were investigated. Viewing a light shaded relief model of the DEM was useful; by varying the elevation and direction of the illuminating light source it was possible to illuminate different sections of the grooves. However, it was impossible to select a light direction that identified all features at one instance. It was realised that some way was needed to separate the small topographic variations created by the engraving process (elevation range: 10 mm) from the overall topographic variations of the natural rock surface (elevation range: 0.3 m). LPS is a software module within the larger 'IMAGINE' package distributed by Leica Geosystems. One of the features of IMAGINE is the ability to write software scripts to perform a sequence of diverse image processing functions. One such 'spatial model' was developed to identify and accentuate the desired engraved features. In this (Fig. 6), the broad morphology of the rock surface is created by smoothing the original DEM using a large 'low-pass' filter (11 × 11 pixels). This smooth surface is then subtracted from the original DEM to generate a new DEM image in which the engraved grooves alone represent the dominant morphological features (Fig. 7). The tool effectively isolates data at one spatial frequency (i.e. the engraved rock art) at the expense of the surface form at other unwanted spatial frequencies (i.e. the general rock surface).

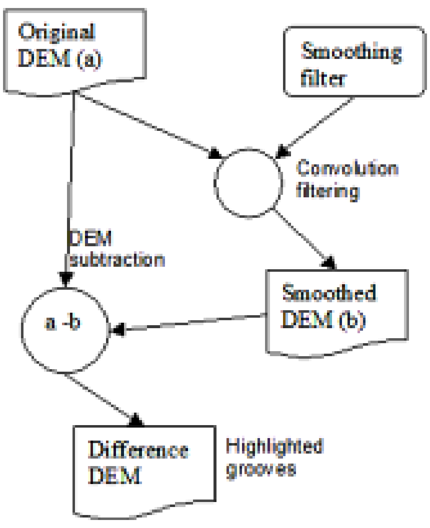

Figure 6. *Spatial model to isolate petroglyph.*

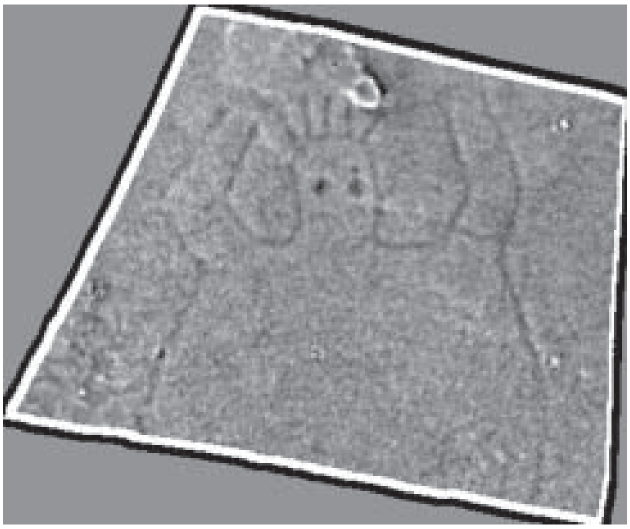

Figure 7. *Engraved features identified, Big Fella site.*

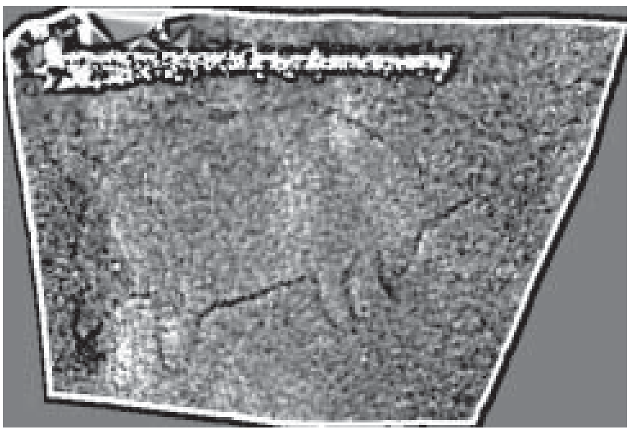

Figure 8. *Engraved features, Zygo site.*

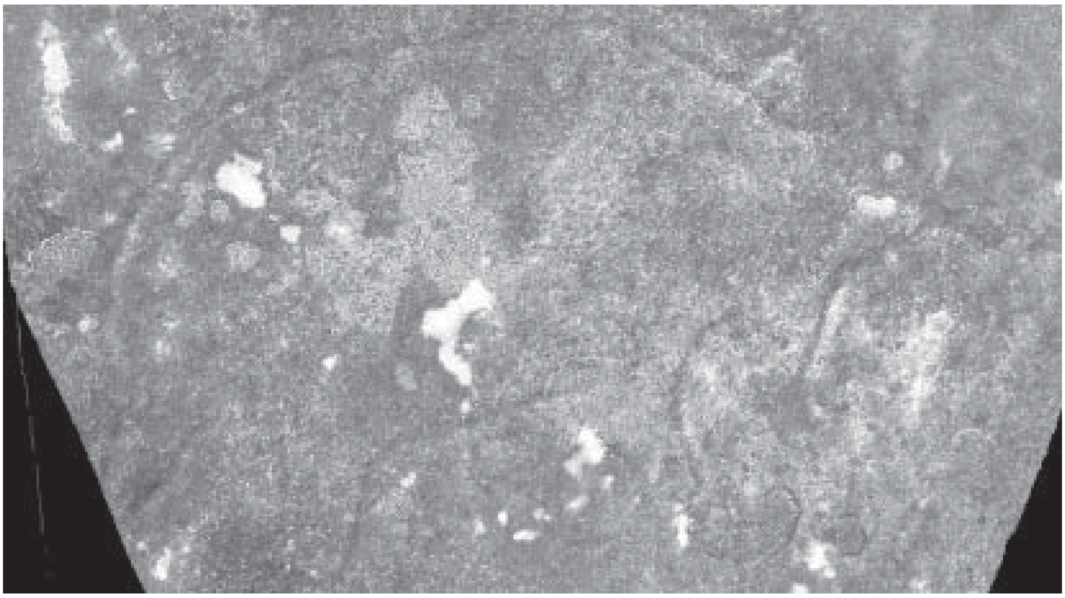

Figure 9. *Greyscale orthophoto, 'dry' Zygo site imagery.*

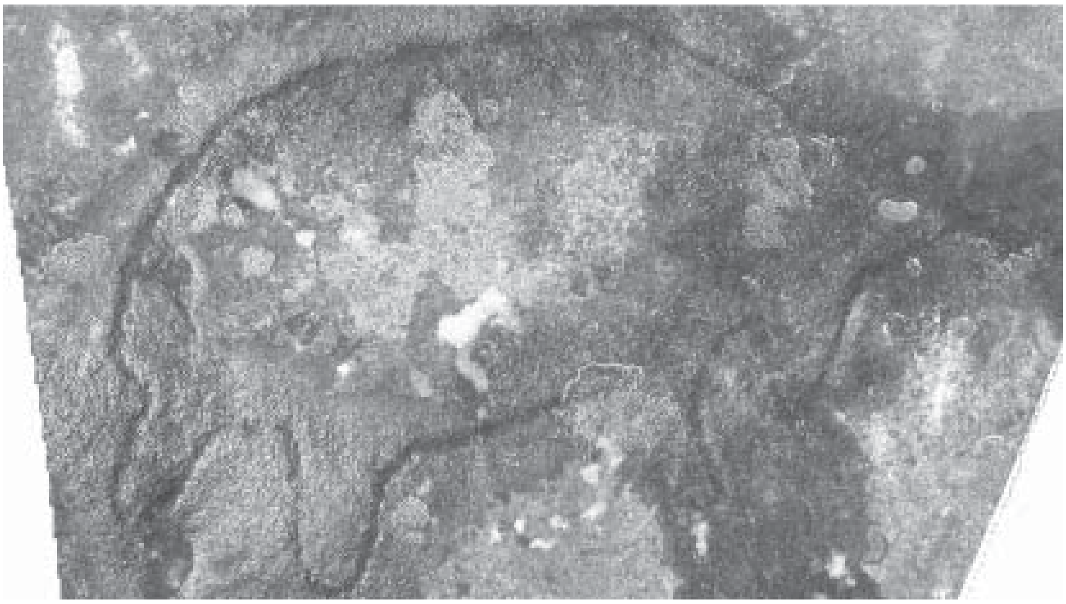

Figure 10. *Colour orthophoto, 'wet' Zygo site imagery (see colour version of this image on back cover).*

The same spatial model was applied to the larger Zygo feature (Fig. 8) but was less successful in isolating the grooves. The Zygo feature was larger, the scale of the imagery smaller and so the final resolution of the measured DEM was 8 mm, coarser than the Big Fella DEM. The width of the engraved features is typically 10–20 mm and consequently a DEM of 8 mm resolution is only just sufficient to record the morphology that is required. The issue of DEM resolution is considered further in the discussion section.

Orthophoto generation and Virtual Reality modelling

Orthophotographs were generated for both sites using both greyscale imagery and colour imagery which had been acquired when the feature was both dry (Fig. 9) and had been wetted (Fig. 10, see colour version on back cover). It is apparent how the petroglyph is more visible in the wet imagery when acquired in colour, compared to the dry greyscale imagery used to create the DEMs. The real significance of the orthophoto is the removal of relief and tilt distortions providing an image with map qualities. For example, horizontal distances between features can be directly scaled from the orthophotograph. Of perhaps greater significance is the combination of the orthophotograph with the DEM, which allows the object to be analysed in three dimensions. In the IMAGINE software the DEM and orthophotograph can be loaded into a package called VirtualGIS which allows 3D interrogation and inquiry (Fig. 11, see also back cover) and also enables the production of 3D fly-through sequences (low resolution example: *http://civil-unrest.lboro.ac.uk/cvjhc/Images/bigfella_compressed 2.avi*). Various light models can be applied and different layers of data visualised from any perspective.

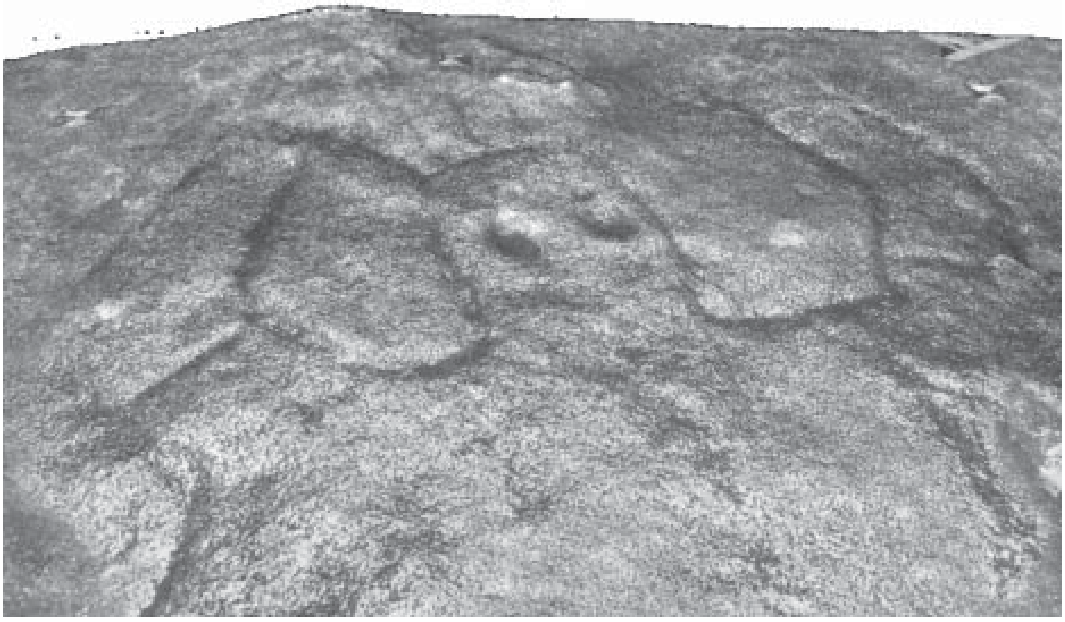

Figure 11. *3D perspective view of DEM and orthophoto, Big Fella site (see colour version on back cover).*

Discussion

Accuracy of DEM data — Nikon versus Kodak versus Total Station

The accuracy of the digital elevation model (DEM) was assessed by comparing the data extracted using the Nikon camera with two other datasets. Initially, the Nikon DEM was compared with a similar high-resolution DEM extracted using the Kodak DCS460, the camera with proven photogrammetric capabilities. Additionally, the Nikon DEMs were compared with the dataset derived using the motorised Leica Total Station, data independent of any photogrammetric measurement.

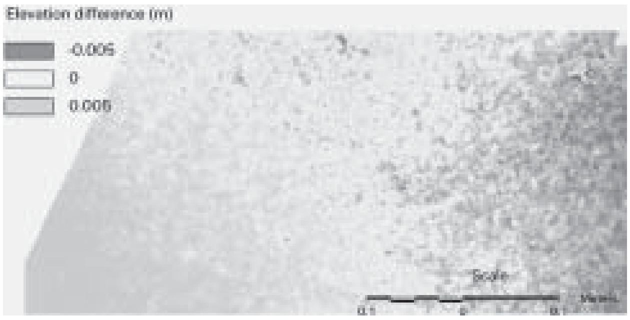

Figure 12. *DCS460 — Nikon Coolpix 3100 (see colour version on back cover).*

Nikon versus DCS460

DEMs were extracted at high-resolution (5 mm) using LPS and imagery acquired with both the Nikon and Kodak. To allow direct comparison at every sampling point, one DEM was simply subtracted from another, creating a new 'difference surface'. Figure 12 (for colour version, see back cover) represents the comparison, with red pixels indicating negative height differences of 5 mm; green pixels representing positive differences of 5 mm; white pixels indicating identical elevations; and, lighter colours indicating differences within these limits. Figure 12 indicates that each camera has captured both the gross morphology defined by the rock surface and the engraved grooves, to a similar level of accuracy. The more discerning eye would also detect a minor trend between the different surfaces, although this is less than 5mm across the entire measurement area.

Nikon versus Total Station

The motorised Total Station and reflector-less EDM had been used to capture a coarse resolution dataset directly in the field. Time constraints allowed only a small area to be measured (1.6 × 0.7 m), located across the 'face' and 'upper torso' of the Big Fella petroglyph. The reflector-less EDM measurement procedure is very slow, requiring approximately eight seconds to measure each point, and consequently only 460 points were measured at an approximate density of 50 mm. This occupied the Total Station for approximately one hour, although fortunately the measurement process was fully automated.

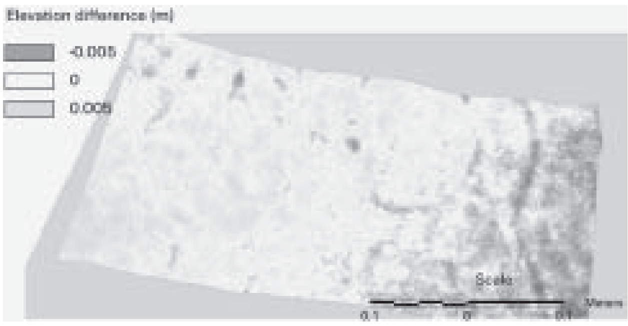

Figure 13. *Total Station — Nikon Coolpix 3100 (see colour version on back cover).*

The measured Total Station data was compared with the photogrammetric datasets through the same subtractive process adopted previously. The difference surface is again represented (Fig. 13, see colour version on back cover) with green and red pixels indicating extremes in the range of ± 5 mm. As in the comparison between the Nikon

Figure 14. *Roland PIX-30 motorised profiler with grooved sandstone slab.*

and the DCS460, a minor trend in the surface can be detected, suggesting that the surface measured using the Nikon camera is slightly warped. However, these differences are small, within the range of 4 to 6 mm. What is more interesting is the sudden appearance of the Big Fella figure in the difference surface (Fig. 13). On reflection, its appearance is entirely predictable and arises due to the contrasting density between the two datasets. The Nikon DEM was captured at 5 mm resolution, sufficient to record the engraved grooves. In contrast, the Total Station DEM was derived from a 50 mm resolution dataset, only adequate to record the gross morphology of the rock surface. When these two surfaces are subtracted from one another, the difference in the two spatial frequencies is highlighted and consequently, the petroglyph appears. In fact, the approach is very similar to that adopted to identify the petroglyph using the spatial model tool (Fig. 6) discussed earlier (Fig. 7). The same gross morphology is created by the smoothing procedure as is effectively recorded by the Total Station. This observation demonstrates forcibly the need to capture data at fine enough grid spacing, an issue that is examined in the following section.

Density of DEM data — lab tests on sandstone block

During development of the photogrammetrically based recording methodology, it became apparent that DEM density was an essential parameter affecting whether petroglyphs can be recorded successfully using such a 'morphological' approach. If the DEM density is insufficient, then detailed morphological investigations, such as querying the width and depth of grooves, will not be feasible. If DEM resolution is insufficient for detailed morphological analysis, it will be still appropriate for production of high quality visualisations and generation of 'fly-through' models.

In order to investigate the issue of DEM density further, laboratory experiments were carried out using a piece of flat sandstone which had been mechanically engraved with grooves of known dimensions. A local funeral mason was approached and a waste piece of sandstone (0.3 × 0.15 m) was engraved with three parallel grooves 7 mm in width and between 2–3 mm in depth, each cut with a differently shaped cross-section. A Picza (PIX-30) 3D Scanner manufactured by Roland DG Corporation of Japan (Fig. 14) was used to measure a 1-mm-resolution DEM to represent the surface of the sandstone block. This instrument uses a mechanical probing device and is consequently very slow, requiring 20 hours to record the surface. Each individual elevation was measured very precisely (± 0.25 mm) and therefore provided a good opportunity to test the accuracy and assess data sampling issues. Imagery of the sandstone block was acquired using the Kodak DCS460 camera from a distance of 0.4 m, which allowed a DEM to be extracted at a resolution of 1 mm also. Figure 15 represents a profile through both the photogrammetric and 3D scanner datasets (exact position marked on Fig. 16). It is most encouraging to see that the photogrammetric dataset agrees very closely with the probe data and that both the depth and shape of the mechanically ground cross-sections are represented. However, limitations in the dataset have to be recognised. Figure 16 is a greyscale representation of the photogrammetrically acquired DEM and the clean edges of the grooves are not as sharply delineated as may perhaps be hoped for. It is important to recognise that any measurement method can only create a 'sample' of the full surface population. If the sample is of sufficient density for the envisaged measurement task, then the record may be judged successful. However, the converse is true also.

In the context of recording engraved rock art and based upon the empirical tests conducted, it is suggested that the DEM resolution needs to be at least half of the width of the smallest groove that is required to be represented in the

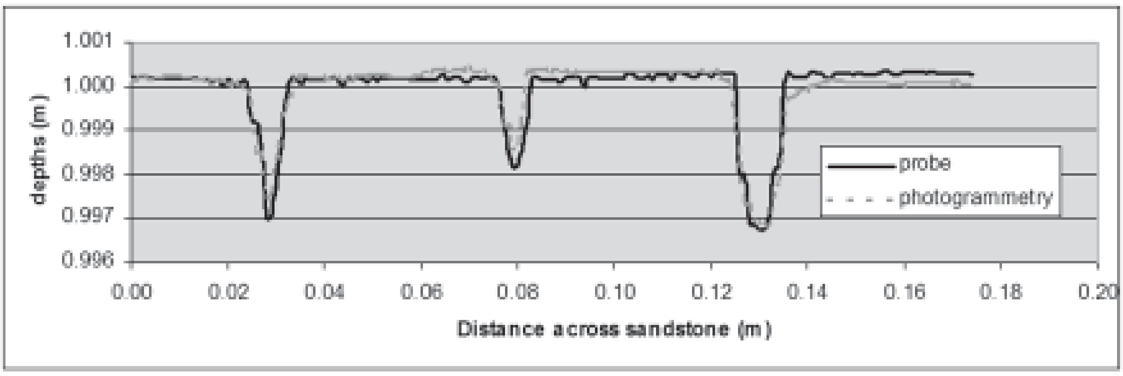

Figure 15. *Cross-section through motorised profiler.*

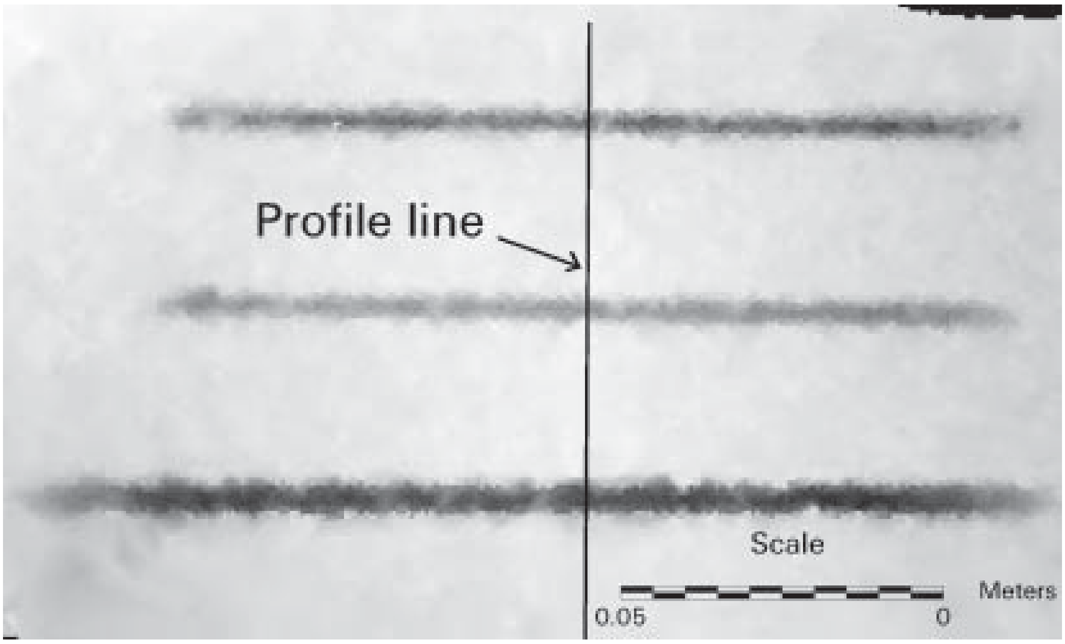

Figure 16. *DEM of sandstone test block derived by photogrammetry, 1 mm resolution.*

DEM. It is particularly satisfying that this rule agrees exactly with the well-known Nyquist theorem (Weeks 1996) — an important limiting model that transcends many scientific disciplines. The theorem stipulates that to represent the spatial details of an original continuous-tone image fully, the image must be sampled at a rate of at least twice that of the highest spatial frequency contained in it (Weeks 1996). Two samples will then record each detail, ensuring that the finest dark-to-light-to-dark detail is captured and the Nyquist frequency is the term referred to in this sampling rate (Weeks 1996). This sampling frequency limit should be regarded as the absolute minimum, as the results achieved for the Zygo test site suggest (Fig. 8). Here the DEM resolution was only 8 mm, approximately half of the width of the engraved grooves and hence some sections of the grooves are not recorded adequately. In the case of the sandstone block, an inadequate sampling resolution would prevent differentiation between the shapes of the cut grooves.

Precision of DEM data

A related constraint is the precision of the extracted height data in relation to the depth of the engraved grooves. If the indentations are shallower than the precision of the photogrammetrically derived height points, then the petroglyph will not be recorded satisfactorily. In the tests conducted on the sandstone test sample (Fig. 13), the grooves were cut to the depth of 2–3 mm. The precision of the photogrammetric DEM was ± 0.15 mm and therefore appropriate to record these grooves, as demonstrated by the cross-section through both the photogrammetric and independent profiler datasets (Fig. 15). The precision of a photogrammetrically acquired DEM is strictly a function of the focal length, camera to object-distance, base/distance ratio and the precision of measurement in the image plane (Ogleby and Rivett 1985). However, for stereo digital imagery this broadly equates to the physical size of an individual pixel on the object — simply a function of the focal length, camera-object-distance and sensor resolution. For the Big Fella and Zygo sites, the precision of the acquired DEMs is conveyed in Table 1.

As expected, Table 1 demonstrates that the high-resolution (6 mega-pixel) DCS460 camera equipped with a 24 mm lens is capable of generating higher precision DEMs than the lower resolution (3 mega-pixel) Nikon Coolpix 3100. The issue of DEM precision can again be related to classical sampling theory, notably signal/noise ratio. The desired 'signal' corresponds to the grooves that need recording and 'noise' corresponds to DEM precision. If the precision/noise is too large relative to the signal/grooves that need representing, then the recorded dataset is of reduced value. It is suggested that using camera technology currently available and at camera-objects heights up to 2 m, that grooves must be at least 2 mm deep to be recorded using the photogrammetric approach outlined here. Petroglyphs with grooves less than 2 mm in depth can still be

Site	Camera-object distance (m)	Nikon DEM Precision (mm)	DCS460 DEM Precision (mm)
Big Fella	1.4	±0.6	±0.4
Zygo	1.6	±0.7	±0.6

Table 1. *Precision of acquired DEMs.*

recorded, although only by using a longer focal length camera setting or acquiring imagery at a closer camera-object distance.

Strengths of the developed system

The system developed has many benefits to offer rock art recorders. Image acquisition is based upon the latest digital camera technology which is becoming ubiquitous and inexpensive; such cameras are also portable, easy to use and sufficiently robust for fieldwork. Significantly, the resolution and precision of derived data is dependent upon the resolution of the sensor and scale of the imagery. Sensor resolution will undoubtedly increase and although a 3 mega-pixel camera was used to conduct the tests described, a 5 or even 6 mega-pixel camera would perhaps be the recommended entry point today. This increase effectively doubles the density of measured surface data and improves the precision of data that can be potentially derived.

The measurement system takes advantage of fully automated DEM generation methods available in photogrammetric software packages, which rely on identifying simple texture in the overlapping images. Thousands of *xyz* coordinates can be generated in just a few minutes, which allow the object to be represented accurately. This contrasts markedly to the approach adopted by Simpson et al. (2004), which requires manual targeting of the object using stick-on targets and manual measurement methods. In addition, the required functionality is available in commercial photogrammetric software packages that have matured significantly since their original development and promotion 10–15 years ago. This widespread availability and comparative simplicity provides the field archaeologist with distinct advantages over related approaches that have been promoted recently (e.g. Pollefeys et al. 2003; Mueller et al. 2004), which use embryonic and less accessible software.

Conclusion

An efficient and effective method of recording petroglyphs using digital photogrammetry has been presented. The approach takes advantage of the new range of inexpensive digital cameras, which, if calibrated, can produce accurate 3D data. Appropriate photogrammetric software is capable of generating thousands of surface points fully automatically and orthophotographs, which, when combined, can be used to produce accurate Virtual Reality models. For most petroglyphs, the required fieldwork can be conducted by non-photogrammetrists using lightweight, portable and inexpensive equipment. At the time of writing (Dec. 2004), there remains some concern that software costs will restrict the use of this technique to larger organisations that can budget for the relatively high cost of the required software.

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