MODELING AND VISUALIZATION OF ABORIGINAL ROCK ART IN THE BAIAME CAVE

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ABSTRACT:

A technique to digitally document and thereby permanently preserve prehistoric rock art has been developed. Laser scanning and texture mapping from digital images were used. Methods involving texture mapping require the exact relationships between the image and geometrical sensors. For geological structures, such as caves, the distinctive features required for registering the texture with the geometric model are difficult to find and extract. The developed technique combines a photogrammetric bundle adjustment and surveying observations to specific detail points to register the images with the scanner data, rather than searching for individual corresponding points. The technique is implemented and tested on Aboriginal painting at the Baiame rock art cave in New South Wales, Australia. The result is an extremely realistic virtual tour of the cave and its important rock art.

1. INTRODUCTION

Aborigines, the indigenous people of Australia, have the longest continuous cultural history, dating back some 60,000 years. It is widely thought that they used rock art to represent and communicate their understanding of the world and reflect their spiritual and religious life. Their rock engravings and cave paintings are an indispensable source of information for our understanding of prehistoric living. However, most Aboriginal cave drawings (figure 1) are located in unprotected environments (figure 2) and are subject to environmental deterioration and vandalism. The surviving examples are now usually located in remote areas, which make it difficult for many to experience. In Europe, most caves with historic rock art have been closed to the public since the 1970s in order to protect them from further deterioration. In some places, for example in Canada and China, some rock art has disappeared permanently under water by hydro or lumber dams. Over the past decades, several studies have made compelling arguments for conserving rock art [Taylor et al, 1975, Clark, 1977].

Figure 1: Aboriginal rock art: Baiame, the sky god of several tribes of New South Wales

It is therefore essential that rock art be accurately recorded, for conservation and studying by historians, archaeologists, the general public and future generations of Aboriginals themselves.

Figure 2: Part of the Baiame cave

Standard recording techniques, mainly tracing and photography, do not allow a full and realistic experience. Traditional measurement techniques, like surveying and photogrammetry, cannot capture all the details of irregular surfaces. Only complete 3-D geometry and color will allow all the possibilities of completely studying, comparing, and even replicating the rock art in its natural environment. With detailed 3-D recording, it becomes possible to study the statistical relationships between various art elements using derived spatial measurements. Lighting simulation is enhanced with a complete 3-D model, thereby improving the ability to understand and appreciate this artwork as it was intended. Understanding and interpreting the meaning of rock art remains a challenging task and having a complete, accurate, and realistic recording of the art and its surroundings can help current and possibly future research requirements.

In the following sections a detailed description is presented of our approach to rock art 3-D reconstruction. Section 2 provides an overview of cave art recording techniques. This leads to the problem definition and description of the proposed solution in the third section. Section 4 describes this solution in some detail. The modeling of the Baiame cave using this multi-technique approach is presented in section 5 and the paper concludes with a short discussion in section 6.

2. ROCK ART RECORDING TECHNIQUES

In this section, we will briefly describe the most common of the many varied techniques of recording rock art. It will then become obvious that digital 3-D recording is a most appealing approach. A good bibliography of available techniques, from early 20th century to 1990 can be found in [Wainwright, 1990.]

2.1 Standard Methods

Photography, complemented by direct tracing, field notes, reports and forms, sketching, and some measurements, is the standard procedure of recording rock art [Taylor, et al, 1977, Rosenfeld, 1977, Wainwright, 1990, Bertilsson, 2001]. Tracing may not be possible for many surface locations, requires direct contact with the art that may lead to damage, and is error prone. The data collection techniques rely on the notes and description of the person carrying it out. They are subjective, affected by the environmental conditions and visibility, and many artworks can be easily missed. They are also extremely time-consuming, thus it may be impractical to comprehensively document a large site. All these standard methods do not allow the viewer to fully interpret or enjoy the art. The lack of geometric shape does not allow interaction or viewing from different directions or under different lighting conditions. No selective measurement or possibility of creating faithful replicas is possible.

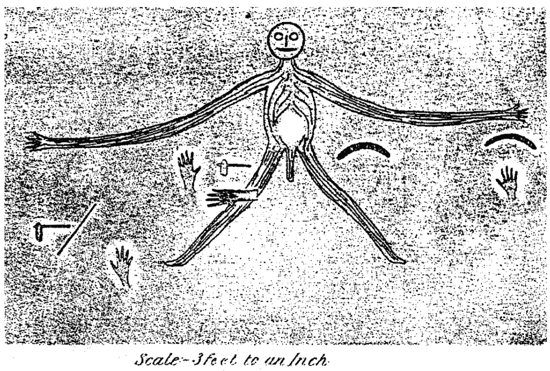

Figure 3: Traditional 19th Century recording of the Baiame cave painting (from Mathews, 1893)

Full understanding of the art is hampered by traditional techniques since the original artists often incorporated natural 3-D shape features of the rock into their drawings. The comparison of similar rock art styles from different sites will be limited. This lack of geometric information also applies to more recent imaging techniques, like panorama or image-based rendering.

2.2 Surveying and Photogrammetry

For decades surveying and conventional photogrammetry have been used to geometrically document rock art [e.g. Atkinson, 1968, Rivett, 1983, Ogleby, 1991, Ebert and Paiva, 1997, Cooper, 1998, Fryer, 2001]. Lately, image-based modeling and rendering techniques were used on China's Dunhuang caves [Lu and Pan, 1999]. Those caves have more regular surfaces and richer texture than most of Australia's aboriginal art caves. Photogrammetry or image-based modeling methods alone will have many problems since there are no sharp edges or sufficient texture to extract and match between images. To get sufficient points to fully describe the surface geometry, automatic matching will be necessary for practical reasons [for example, Ferrari et al, 2003]. However, the lack of well-defined features, combined with the natural illumination variations in above ground caves will challenge any automatic matching technique. Moreover, there are no geometric constraints, like flat surfaces or straight edges, to help the matching. Worse yet, in most natural settings, the terrain, rocks, and trees make it impossible to take images from suitable positions to allow for a proper image sequence. This results in images being taken at widely varying orientations thus causing features to appear dissimilar. Thus the usual color, shape, and geometric constraints necessary for successful matching will be absent. Occlusions and lack of known surface shapes and vanishing lines will also prevent extraction of 3D from single images, so gaps or holes will be formed. Therefore, surveying, photogrammetry and image-based methods alone will not show all the geometric details and will generate only sparse data. This data will be ineffective for computing the realistic appearance of rock surfaces.

2.3 Range-Sensor / Laser Scanners

Laser scanners can potentially provide complete and accurate representation of highly irregular surfaces. Combined with color information, either from the scanner itself or from a digital camera, a realistic-looking model can be created. Ideally the scanner should be tailor made to the specific requirement of the application. The accuracy at the given range and the capture of both geometry and reflection or intensity are key scanner properties. Also due to size, geometric configurations, and occlusions, it is usually necessary to use multiple scans from different locations to cover the entire scene. Aligning and integrating the different scans, for which many techniques are available, will also affect the final accuracy of the 3-D model.

Literature searches indicate that laser scanners are not yet widely used for rock art or cave recording. Donelan, 2002 reported using the Minolta VI-700 scanner to physically replicate the cave at Altamira in northern Spain. Numerous modeling and CAD software tools were used and the data was fed into a milling machine to create the cave replica. The rock art was physically painted onto the replica.

Laser scanning may also be the solution to recording petroglyphs (rock carving), which may be difficult to discern from images. Highly accurate scanners with low noise level can create 3-D geometric models from which petroglyphs can be visible when manipulating the model at close range or by carefully simulated lighting.

From the above brief analysis of the recording techniques, we can conclude that the laser scanning technology, combined with an appropriate color or texture acquisition technique, is the most promising approach to completely, accurately, and photo-realistically document rock art. This is the approach adopted and further developed for this application based on the experiences previously gained from many other laser-scanning projects [e.g. Beraldin et al, 2002].

3. PROBLEM DEFINITION AND PROPOSED SOLUTION

Issues related to laser scanning, specifically for rock art recording, are described in this section, along with the approach taken to address these problems.

3.1 Issues Relating to Scanning and Texturing

3.1.1 Texture / Color Acquisition: Intensity or color provided by some scanners via a color channel is usually not of the desired quality. Only at the scanned points is color provided, so textures between those points will not be captured. Since the details of the textures are of great interest, this approach is inadequate. Another alternative is to attach a high-resolution camera with the scanner and take a registered image with each scan. However, this will limit the flexibility to take the image at the best lighting conditions and have full control on the parameters that affect the sharpness and color quality. It is therefore more useful to acquire geometry and texture by two independent processes. It is often desirable to move around and take images from best possible positions or at closer range than the range from which the scanning is most effective. Rock art can be subtle and may need to be viewed from specific positions, directions and distances at varying lighting conditions to be clearly visible.

3.1.2 Texture and Geometry Registration: In order to register the texture with the 3-D geometry, we need to accurately determine the camera's internal and external parameters. Interactive selection of corresponding points in the 3-D geometric model and the digital image usually does this [Beraldin et al, 2002]. Some attempts have been made to at least semi-automate this step [e.g. Neugebauer and Klein, 1999] but in our case the nature of the features made such techniques unreliable. Even with manual correspondence, the lack of suitable features will impede the registration process.

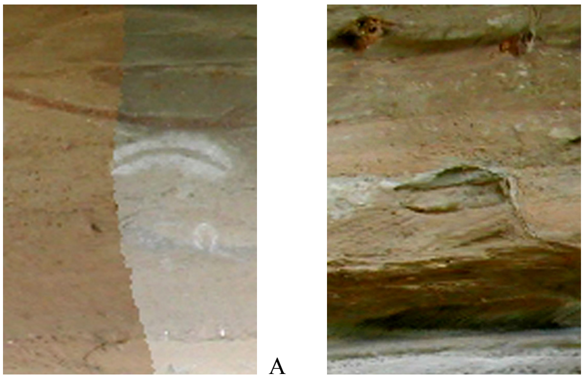
A B

Figure 4: (A) Two adjacent textures from different images, (B) Texture should match geometric details

3.1.3 Noise Level: Due to the cost of highly accurate scanners that can cover the volume of a cave, one may be forced to use a lower cost scanner, which usually has a high noise level. This will require filtering the noise or smoothing of the resulting scans [Taubin, 2000]. Without such a process the triangulated mesh will form rough and unrealistic surfaces. However, the filtering will also remove those smaller geometric details which are close in size to the noise. In case of rock surfaces, this means that corners and edges could dissolve. Inaccurate corresponding points, even by a small amount, between the images and the model will result in inaccurate registration and visible anomalies such as textures from multiple images not aligning, or color projected on the wrong geometric detail [El-Hakim et al, 2003b]. Figure 4-A shows a case where the two are properly aligned and Figure 4-B shows a case where the textures are projected on the correct geometric details.

3.2 Our Approach

The approach presented addresses the issues identified above. Since every site will be different, especially in the quality and quantity of the textures, the developed technique is general and can be applied to any site and with any scanner. Specifically the technique:

- Allows imaging for texture maps to be carried out separately from the scanning
- Does not rely on extracting features to register the texture images with the geometry
- Does not require a highly accurate scanner. It may be difficult to justify the high cost of a precise scanner since high geometric accuracy on rock surfaces may not be needed.

The technique combines a photogrammetric bundle adjustment using surveyed points on the texture images with the laser scanner data. Surveying serves to set up the reference frame for the texture images and for the scanned points. The surveyed points should be on both textural and geometric discontinuities. A benefit of the surveyed points is that when used as control points for the bundle adjustment they improve the accuracy and limit error propagation, even when the geometric configuration of the images is poor. The details of the approach are given in the next section.

4. DETAILS OF THE APPROACH

Photogrammetry and laser scanning have been combined, in different ways, in several projects. Photogrammetry has been used to model the main shapes while laser scanning captured the fine details [El-Hakim et al, 2003a]. Photogrammetry has also been used to register the laser scans in a single coordinate system [Guidi et al, 2002]. Here, we use photogrammetry and surveying to register the texture images with the geometry. Figure 5 shows an overview of the steps for creating the textured 3-D model. All the steps can be done with commercially available software tools.

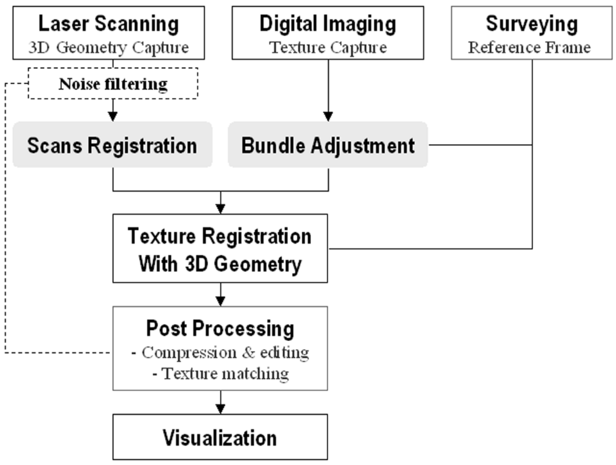

Figure 5: The 3-D reconstruction pipeline.

4.1 The Photogrammetric Bundle Adjustment

Images are taken at locations suitable for texture mapping and to cover all the surfaces of interest. The terrain and trees or other occluding objects limit the possible imaging locations. Therefore, the camera configuration is unlikely to be ideal for bundle adjustment (see Figure 6 for the actual camera locations for the Baiame cave). However, the use of surveyed points as control points will decrease the error propagation. The camera internal parameters, at the settings used in the field, were determined in a separate calibration process since the camera configuration would most likely not allow reliable self-calibration. The camera external parameters as well as the 3-D point-coordinates from the bundle adjustment will be in the coordinate system defined by the surveyed points.

Figure 6: Actual camera locations.

4.2 3-D Geometric Modeling

The procedure for creating a triangular-mesh model from 3-D images is summarized in Figure 7. A single scan is usually not sufficient to cover an object. The number of necessary scans depends on the shape of the object, amount of occlusion and obstacles, and the object size compared to the sensor range. The 3-D data must then be registered in one coordinate system. Most registration techniques are based on the iterative closest point (ICP) approach [Besl and McKay, 1992]. For the approach to converge to the correct solution, it needs to start with the scans approximately registered. Once all the data is registered, it can then be used for modeling. If the 3-D data is presented as a set of registered scans it is easy to create a triangular mesh by simply triangulating each scan. However, since there is often a sizeable overlap between the scans from different view-points, a mesh created this way will have many redundant faces. It is desirable to create a non-redundant mesh with no overlapping faces [Soucy et al, 1996]. Once the model is created, all its points are transformed by a similarity transformation to the coordinate system defined by the surveyed points, using a minimum of 3 surveyed points (usually 4 to 6 points are used). These points are preferably selected on sharp surface discontinuities.

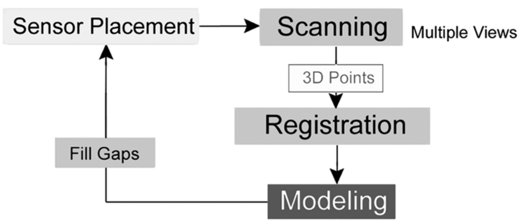

Figure 7: General steps for modeling scanned data.

4.3 Registration of Texture with Geometry

Normally, a few join points between the images and the geometric model are extracted for the registration. But in the procedure here, this is not necessary. After steps described in sections 4.1 and 4.2, the camera parameters and the 3-D coordinates of the geometric model are already in the same coordinate system (defined by the surveyed points).

4.4 Post Processing and Visualization

In most cases, some post processing in the form of editing or compressing the geometric data is needed. Compressing, to reduce the model into a manageable size for manual interaction, should be done after texture mapping so the quality of the texture is not affected [Soucy et al, 1996]. Another post processing operation is color correction, used, for example, to match adjacent textures taken from different images. The variation between images will usually be significant in an outdoor environment where lighting is not controlled (see Figure 4-A above for an example of differences between two images). For more details on procedures developed earlier for texture correction and visualization, see [El-Hakim et al, 2003b]. The approach in section 4 will be tested on the Baiame cave modeling project in the section 5.

5. MODELING THE BAIAME CAVE

The laser scanner used is the *Riegl*® LMS-Z210i (Figure 8). This is a time-of-flight scanner with range from 4m to 4000m and field of view of up to 80 deg. by 360 deg. It provides range and color information, achieved by a one pixel digital camera [Reichert et al, 2001] with roughly the same field of view as the scanning. However, the color information obtained was not usable, probably due to poor lighting conditions in the cave. The quoted accuracy is ±25mm under normal conditions. The data in this study estimated a noise level of ±30mm. We used a *Nikon*® coolpix® digital camera for texture imaging and the *ShapeCapture*® software for camera calibration and bundle adjustment [ShapeQuest Inc., http://www.shapecapture.com]. *PolyWorks*® software was employed for the geometric modeling [Innovmetric Software Inc., http://www.innovmetric.com]. Nineteen points located at shape discontinuities were surveyed with a *Leica*® reflectorless total station to 2-3 mm accuracy. It was anticipated that most of them would be detectable in the 3-D surface data from the scanner. Although only 11 of them could be detected with certainty, this was still a sufficient number for the bundle adjustment and for transferring the scan data to the reference frame.

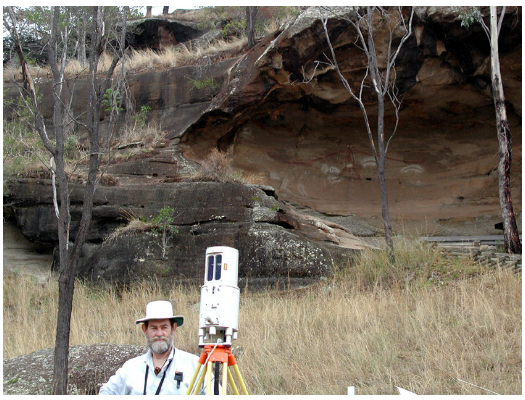

Figure 8: The *Riegl*® laser scanner.

To evaluate the accuracy of the bundle adjustment, initially only 3 control points were used with the remaining points as checks. The average error was 42 mm, being largest in the X coordinate. This reflects the poor geometric configurations of the camera locations (Figure 6) and the lack of sufficient well-defined features. For the final adjustment, all 11 control points were used. The standard deviations of the computed 3-D coordinates were: **13**mm [X], **9**mm [Y], and **11**mm [Z].

For comparison with the laser scanner model, an image-based model from the digital images and the 3-D points resulting from the bundle adjustment was created. This illustrates the problems associated with image-based modeling on irregular surfaces where only a few distinctive features allow the creation of a small number of 3-D points. Figure 9 shows the geometric details are very approximate and the model does not adequately represent the real cave shape, even with the texture applied.

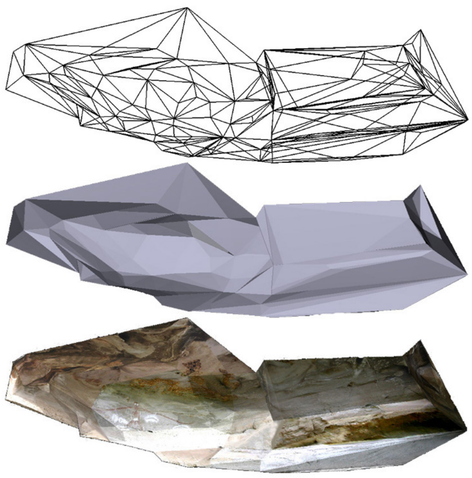

Figure 9: The model created from image-based modeling only: wire-frame (top), un-textured (center), and with textures.

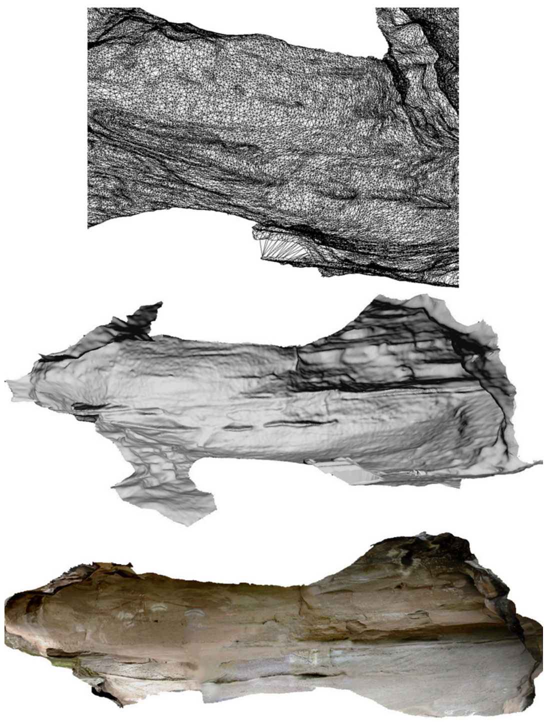

Figure 10: The final model: part of the wire-frame (top), un-textured (center), and with textures.

By contrast, the model created by the laser scanner and the approach described in this paper (Figure 10) shows all the fine geometric details (over 400,000 triangles, compared to less than 1000 in the image-based model). When the textures are placed on the geometry, it is clear that it is a complete representation of the Baiame cave and we can experience a true-to-life journey through the model. This model can be manipulated on a PC screen with a VRML viewer, or in a large VR theatre where more immersion can be experienced. Another product of the project is a movie that takes the viewer through the cave with appropriate commentary and background music.

6. CONCLUDING REMARKS

In this paper an approach is presented to creating detailed and realistic 3-D models using a combination of laser scanning, bundle adjustment, and surveying. The technique achieves the texture mapping without extracting common points between the texture images and the 3-D geometric model. There is no need for artificial targets in either 2-D or 3-D to register the data. The Baiame cave project offered an excellent experiment to test the effectiveness of the approach in a real unstructured environment. In fact, the laser scanning, surveying and digital images were gathered in Australia (by Fryer) and the processing was independently done in Canada (by El-Hakim and Picard). To have produced a realistic result under these conditions is testament to the robustness of the approach adopted!

There are still some issues to address. One of these is how to define the optimum accuracy needed to achieve the objectives of visual fidelity of the art and relevant geometric relationships rather than a high local metric accuracy of the cave walls. What should be the optimum accuracy, or the level of detail (spatial resolution), of the 3-D points which will translate into the desired visual fidelity? All the factors contributing to accurate registration of the images to the laser scans must considered, otherwise textures will be projected onto the wrong part of the surface. There will be visible mismatches and discontinuities along the borders of textures from different images. Therefore, even though the rock surfaces may not need high accuracy, low accuracy will garble and distort the texture mapping. Another issue concerns the several manual operations required. In particular, the extraction of the surveyed points from the 3-D geometric data remains dependent on human interpretation and can be error prone. More than 40% of the surveyed points could not be distinguished with sufficient confidence from the geometric data and were discarded. Although these problems remain, this first project has illustrated the effectiveness of this technique for recording rock art and provided objectives for future work.

Acknowledgements

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Postscript. The painting of Baiame (Figure 1) has been subject to various interpretations, but commonly it is suggested that: he has two large eyes to see everything; no mouth so he cannot speak ill of people; his arms are long (each 5 meters) and outstretched to embrace all people; and, he has enormous powers coming from the "fire" in his stomach.

References

Atkinson, K.B., 1968. The recording of some prehistoric carvings at Stonehenge, *The Photogrammetric Record* 6, April, pp. 24-31.

Beraldin, J.-A., Picard, M., El-Hakim, S.F., Godin, G., Valzano, V., Bandiera, A., Latouche, C., 2002. Virtualizing a Byzantine Crypt by Combining High-Resolution Textures with Laser Scanner 3D Data, Proc. VSMM, Korea, Sept., pp. 3-14.

Bertilsson, U., 2001. Rockcare Tanum Laboratory of Cultural Heritage, *Int. Newsletter on Rock Art* (INORA), 28, pp. 18-25.

Besl, P.J., McKay, N.D., 1992. A method for registration of 3-D shapes, *IEEE Transaction PAMI*, 14(2), pp. 239-256.

Clarke, J., 1977. Deterioration analysis of rock art sites, Proc. Int. Workshop Conservation of Rock Art, Perth, Australia, Sept., pp. 54-63.

Cooper, S.E., 1998. Softcopy Photogrammetry and the development of field methodologies applied to the recording and analysis of rock art, MA Thesis, Univ. of Arkansas.

Donelan, J., 2002. Making prehistory, *Computer Graphics World*, March, pp. 32-33.

Ebert, J.I. and J.V.R. Paiva, 1997. Non-Contact, Real Time Capture of Three-Dimensional Rock Art Data, *GIS/LIS '97* Annual Conference and Exposition Proceedings, Cincinnati, Ohio, October, 136-138.

El-Hakim, S.F., Beraldin, J.-A., Picard, M., Vettore, A., 2003a. Effective 3D modeling of heritage sites, 4th Int. Conf. 3D Imaging and Modeling (3DIM'03), Banff, Canada, pp. 302-309.

El-Hakim, S.F., Gonzo, L., Picard, M., Girardi, S., Simoni, A., Paquet, E., Viktor, H., Brenner, C., 2003b. Visualization of highly textured surfaces, 4th Int. Symposium Virtual Reality, Archaeology and Intelligent Cultural Heritage (VAST2003), Brighton, UK, 5-7 November, pp. 231-240.

Ferrari, V., Tuytelaars, T., Van Gool, L., 2003. Wide-baseline multiple-view correspondences, in Proc. IEEE CVPR, pp. 718-725.

Fryer, J., 2001, Surveyors and Archaeology: Recording timeless treasures. *Geomatics World*, 9(6), Sept.-Oct.

Guidi, G., Tucci, G., Beraldin, J.-A., Ciofi, S., Ostuni, D., Costantini, F., and El-Hakim, S., 2002. Multiscale archaeological survey based on the integration of 3D scanning and photogrammetry, Proc. Int.. Workshop on Scanning for Cultural Heritage Recording, Corfu, Greece. Sept., pp. 58-64.

Lu, D., Pan, Y., 1999. Image based modeling and Rendering for Dunhuang Art Cave, Proc. 6th Int. Conference of CAD & CG, CAD/CG'99, December, Shanghai, PR China.

Mathews, R.M., 1893. Rock Paintings by the Aborigines in Caves on Bulgar Creek, near Singleton*. Journal and Proceedings of Royal Society of New South Wales for 1893*. XXVI: 353-358.

Neugebauer, P.J., Klein, K., 1999. Texturing 3D models of real world objects from multiple unregistered photographic views. *Computer Graphics Forum*, EUROGRAPHICS Proc., 18(3), Sept., pp. 245-256.

Ogleby, C., 1991. Recording Aboriginal Rock Art – Beyond the Tea Towel, 1st Australian Photogrammetric Conf., Sydney.

Reichert, R., Riegl, J., Ullrich, A., 2001. Time-of-Flight Based 3-D Imaging Sensor with True Colour Channel for Automated Texturing, 5th Conf. Optical 3-D Measurement Techniques, Vienna.

Rivett, L.J., 1983. The application of Photogrammetry to the recording of rock art and archaeological sites in Kakadu national park, *Australian National Parks and Wildlife Service Special Publication*, 10, pp. 87-126.

Rosenfeld, A., 1977. Recording rock art – a conflict of purpose? Proc. Int. Workshop Conservation of Rock Art, Perth, Australia, Sept., pp. 54-63.

Soucy, M., Godin, G., Baribeau, R., Blais, F., Rioux, M., 1996. Sensors and algorithms for the construction of digital 3-D colour models of real objects, Proc. IEEE Int. Conf. Image Processing, Lausanne, Switzerland, Volume II, pp. 409-412.

Taylor, J.M., Myers, R.M., Wainwright, N.M., 1975. An investigation of the natural deterioration of rock paintings in Canada, Proc. of the Stockholm Congress: Conservation in Archaeology and the Applied Arts, June 2-6, pp. 87-92.

Taylor, J.M., Bokman, W., Wainwright, I.N.M., 1977. Rock art conservations, Proc. 4th Biennial Conference of the Canadian Rock Art Research Associates – CRARA'77, Oct. 27-30, Victoria, B.C., Canada, pp. 293-324.

Taubin, G., 2000. Geometric signal processing on polygonal meshes. EUROGRAPHICS'2000: State of the Art Reports, Aug., pp. 107-117.

Wainwright, I.N.M., 1990. Rock painting and petroglyph recording projects in Canada, Association for Preservation Technology *APT Bulletin* Vol. XXII, No. 1/2, pp. 55-84.