KEYWORDS: ***Photogrammetry – DStretch – Virtual reality – Bunjil's Shelter – Gulgurn Manya***

STRETCHING THE SURROGATE:
AN INITIAL TEST COMBINING DSTRETCH IMAGE ENHANCEMENT WITH PHOTOGRAMMETRY MODELLING AT BUNJIL'S SHELTER AND GULGURN MANYA, AUSTRALIA

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Abstract. This paper presents the initial results of a digitisation project exploring the combination of photogrammetric modelling with DStretch image enhancement and 3D model display within virtual reality head-mounted displays. Using the sites of Bunjil's Shelter and Gulgurn Manya within or near Gariwerd as case studies, the paper outlines a process for applying DStretch image enhancement to photogrammetry textures and reapplying these textures to the 3D models, allowing a completely DStretch-enhanced 3D model to be viewed within virtual reality. Photogrammetry and DStretch enhancement have long been used in the documentation and analysis of rock art. However, few papers have reported on the potential benefits of combining the two methods, and no Australian papers to date have reported on the display of this combination within virtual reality. Under-discussed applications of photogrammetry are described, and the unique opportunities offered by the combination of the two methods are presented, particularly the ability to digitally trace motifs from the DStretch-enhanced model and separate motifs from the original photogrammetry model. The combination is demonstrated to be feasible at a low cost of time and equipment. Potential benefits of virtual reality display are discussed, emphasising Traditional Owner management, public outreach and education.

Introduction

Recording rock art sites is an essential and longstanding component of ensuring that these data are available for monitoring in the interest of the rock arts' management, preservation, interpretation and research (e.g. Sullivan 1983; Gunn 1995; Loendorf 2001). Rock art visual and spatial data has traditionally been recorded through the manual production of sketches, copies and direct tracings. These traditional methods, however, are now being improved by using digital tracing and 3D digital recording techniques, which have been demonstrated in the past decades to accurately record three-dimensional spatial and visual data (Ogleby 1995; Chandler et al. 2005). In more recent years, the development of structure-from-motion photogrammetry (henceforth 'SfM photogrammetry') has allowed for the creation of highly detailed, immersive and lifelike 3D virtual representations of rock art sites presented on accessible, consumer-grade hardware (as anticipated in Ogleby 1995).

Three-dimensional recording of rock art sites facilitates not only a level of motif identification comparable to field visits to the original site (Jalandoni and May 2020) but also provides unique opportunities for the distribution of visual and spatial data (Blinkhorn 2015), the ongoing management of at-risk sites (Davis et al. 2017), the digital reconstruction of damaged elements (Bea and Angás 2017), and the production of immersive virtual reality (VR) experiences virtually representing sites with restricted access or for public display (Robinson et al. 2015; Davis et al. 2017). This paper initially explores combining two commonly used contemporary recording techniques, SfM photogrammetry and decorrelation image enhancement (DStretch; Harman 2005) and explores the potential for 3D model viewing within a VR head-mounted display (HMD).

Digital recording with photogrammetry allows for producing highly spatially accurate digital surrogates of archaeological sites and materials, including rock art sites. SfM photogrammetric recording is a non-invasive rock art recording technique (Fernández-Lozano et al. 2017), as it requires no direct contact with art panels. Photogrammetric modelling produces not only a visually appealing digital reproduction of the site that has the subjective 'look' of the original (Davis et al. 2017) but, when correctly scaled, it also allows for accurate measurements to be taken from any range of points on the surface including the calculation of the area enclosed within a traced polygon. The inclusion of geospatial data additionally allows for selected points on the model to be identified in geographical space. The shelter models can generate orthorectified images (stitched into an orthomosaic) that accurately display the site from any chosen angle while removing the distortions of perspective that would result from standard photography. They also allow orthomosaics to be produced from viewpoints that are inaccessible to field photography. Orthomosaics contain the same geospatial data that can be obtained from the model and can be imported into GIS programs and databases to enable more sophisticated and ongoing research and management than could be undertaken with traditional recording methods, with no need to repeatedly return to the field, saving time and reducing the potentially damaging impact of field visits on sensitive sites. Photogrammetric modelling creates a rich repository of visual and spatial data that can be retained, easily accessed, distributed, manipulated and analysed.

Digital image enhancement techniques permit the identification, recording and detailed analysis of otherwise significantly faded painted motifs (Harman 2005; Fernández-Lozano et al. 2017). The most commonly used digital image enhancement techniques in rock art recording are Principal Component Analysis (PCA) and decorrelation image enhancement (Domingo et al. 2015). Decorrelation image enhancement converts the colour space of a given image into a new colour space, using a Karhunen-Loeve transform to decorrelate the colour space variables before equalising colour variance and transforming the data back into an RGB colour space (Robinson et al. 2015). This process enhances colour differences, emphasising selected colour tones to make them vividly apparent even when barely detectable to the eye in the original photograph or viewed in person (Domingo et al. 2015). The ImageJ plugin DStretch (Harman 2005) automatically completes this procedure across various selected colour fields, allowing researchers to quickly identify and document faded motifs (Fraile et al. 2016). DStretch enhancement can be applied to image textures or orthomosaics derived from photogrammetric modelling (Bea and Angás 2017), which can be reapplied to the 3D model (Fraile et al. 2016; Jandaloni and May 2020), enabling an entire site to be viewed in a selected DStretch colour space at once. This combination offers significant potential for the virtual analysis of complete models of rock art sites, yet to date appears to have been underutilised, with photogrammetry and DStretch more commonly used in isolation than combined.

Many archaeological sites can not only be difficult to interpret without signage or professional guidance but are restricted from public access due to remoteness, the fragility of the site, difficulty of access, individual mobility issues or cultural sensitivity issues. Rural archaeological heritage distant from urban centres is often underfunded in terms of conservation, access development, and interpretative signposting, which influences the number of people who visit these sites and the degree to which they can comprehend and connect with them, reducing the mental space these sites occupy in the public imagination. This issue has long been noted in the case of Australian heritage (Lennon 2011), creating an imbalance in the importance rural heritage sites hold in public consciousness relative to their importance to Australian history and heritage. Indigenous sites are particularly vulnerable to this underrepresentation, given the low correlation between significant Indigenous sites and major urban post-contact settlements. VR displays of archaeological heritage sites have been proposed as a low-cost means by which rural archaeological heritage can be more widely promoted and distributed when access is restricted and significant funding is not forthcoming (Keep 2022a).

Immersive technologies such as VR displays have long been used as a means to engage audiences with archaeological heritage (for recent reviews see Bekele et al. 2018; Chang et al. 2022; Theodoropoulos and Antoniou 2022), and have previously been explored as a means of data visualisation of rock art sites (Robinson et al. 2015; Bea and Angás 2017; Cassidy et al. 2019) including on Australian rock art sites (Gard and Wyeld 2006; Davis et al. 2017). In the case of Davis et al. (2017), a major benefit of the creation of the VR model was providing members of the Yinhawangka community the ability to virtually tour the Pilbara rock art, which was otherwise difficult to access, assisting Yinhawangka Elders with ongoing management of the site. The Yinhawangka community reported a high sense of presence when experiencing the VR tour, a metric often considered an essential factor in the efficacy of virtual heritage displays to engage users and form an emotional connection (Pujol-Tost 2017).

VR displays of cultural and archaeological heritage, particularly those that are capable of creating an emotional connection with the user (Economou and Pujol-Tost 2008; Katifori et al. 2019; Lacko 2019), have been progressively explored in the 21st century with the technological development and growing popularity of commercially available HMDs as a means of improving learning outcomes (Economou and Pujol-Tost 2008; Merchant et al. 2014; Christofi et al. 2018). VR displays have been demonstrated through experimental studies to create a greater sense of engagement and immersion relative to traditional teaching methods (Merchant et al. 2014), with associated increases in brain activity within regions associated with attention, cognitive processing and memory (Škola et al. 2020). The improved learning outcomes have greater longevity than traditional teaching methods, suggesting these differences in learning outcomes are stable and not merely a temporary result of the novelty of the display (Lacko 2019).

This paper reports on an initial pilot study to test the feasibility of combining photogrammetric

Figure 1. *Bunjil's Shelter from the southwest when first recorded in 1957 (photo: I. R. McCann).*

modelling and DStretch image enhancement on two significant rock art sites in Gariwerd (the Grampians), located on the traditional lands of the Djabwurrung, Jardwadjali and Gunditjmara people. The project aims to explore the ability to display the DStretch-enhanced 3D models of the site within VR and consider whether the display has the potential to assist Traditional Owners and Parks Victoria with ongoing management of the sites, serve as a viable alternative to in-person visits for researchers and interested members of the public who are unable to access the site and act as the basis for public learning and education programs that can promote and assist in interpreting the cultural significance of the sites. To the best of our knowledge, it is the first such combination of photogrammetric modelling, DStretch image enhancement and VR display in Australia.

Description of the sites

Bunjil's Shelter

Bunjil's Shelter (previously recorded as Bunjil's Cave) is in the south side of a granite tor on the lower slopes of the Black Range, 10 km south of Stawell, and 15 km east of Gariwerd and the Grampians National Park (Fig. 1). The paintings consisted of Bunjil and his two dogs in white outline and interior decoration over a solid infill of red. Bunjil is the supreme Being in the cosmology of Victorian Aboriginal people: he created all things and provided the lore and culture for the people (Howitt 1904; see also Smyth 1878). He lives in the sky with his family, where he is all-seeing, and communicates with people primarily at times of initiation. Hence, any image of Bunjil is of particular significance to the local Aboriginal people. Anthropologist A. W. Howitt records that he was told by one of the Mukjarawaint (a branch of the Wotjobaluk speakers around Horsham) that 'at one time there was a figure of Bunjil and his dog in a small cave behind a large rock in the Black Range near Stawell, but I have not seen it, nor have I heard of anyone seeing it' (Howitt 1904: 491; in his original notes Howitt mentions 'dog**s**', plural. Clark 2002). The site was only found and recorded by the Museum of Victoria in 1957 (Massola 1957). More recently, Clark found that 'According to the information given to John Mathew, the rock art site is commemorative — it recalls an event at which Bunjil was killed by a Bunyip and cut into pieces. Through the intervention of birds, he was pieced together and returned to life' (Clark 2017: 192). It is assumed that the stripes and dots on the image of Bunjil represent the scars of the birds' stitching.

Gulgurn Manya

Gulgurn Manya (previously recorded as Flat Rock 1) is at the northern tip of Gariwerd, 40 km NW of Stawell, and 25 km SE of Horsham (Fig. 2). The shelter, 13 × 3 × 2.5 m, has resulted from the horizontal undercutting of a sandstone seam on the northern side of the range, adjacent to an elevated flat rock platform that looks out over the Wimmera plains to the north. No written Indigenous interpretation has been recorded. The site was the sixth rock art site recorded in Gariwerd and the first outside the Victoria Range (Massola 1956). The art of Gulgurn Manya (meaning 'children's hands') consists of 190 images in red: dominated by a large (53 cm) ladder-like design, 103 bars, 23 bird tracks, and 26 handprints. A panel of seven children's hands at the northern end of the shelter is the basis for the shelter's name. While images occur on the rear wall, most are on the horizontal ceiling.

Methods

The two test-case sites for this pilot study were selected for their accessibility, cultural significance and the presence of a range of features that would benefit from photogrammetric modelling and DStretch image enhancement. The sites selected were Bunjil's Shelter and Gulgurn Manya. Bunjil's Shelter had relatively simple geometry that ensured successful photogrammetric modelling and featured both faded original rock art motifs and removed modern graffiti, which were anticipated to become more visible with DStretch enhancement. Gulgurn Manya featured a wider variety of rock art motifs in various stages of

Figure 2. *Gulgurn Manya from the northeast with scrub cover removed by the 1983 bushfires (photo: R. G. Gunn).*

preservation and with notably more complex geometry than Bunjil's Shelter, featuring rock protuberances and overhangs that show evidence of ledge quarrying. It was hoped that the different properties of these sites would provide an initial indication of the level of detail that could be accomplished through photogrammetric modelling without the aid of laser scanning equipment, thereby offering an indication of how future workflows may need to be adapted.

Both sites were photographed using a Sony a7R iii digital camera, which features a high-resolution (42.4 Mp) sensor to produce higher-resolution 3D model textures. A scale bar was included in the photographs to facilitate the scaling of photogrammetry models. A fixed 35 mm wide-angle lens was used to reduce perspective distortions while capturing a relatively wide span per image and to maintain a constant focal length to reduce errors in photogrammetric modelling. Photos were taken with each site in the shade to preclude variations caused by changing light conditions. As an experiment, a ring flash was used when photographing Bunjil's Shelter, while only natural lighting was used when photographing Gulgurn Manya. The variations resulting in the final texture are discussed below. In total, 263 photographs of Bunjil's Shelter and 511 of Gulgurn Manya were taken. Photogrammetric modelling and texturing of each site was completed within Agisoft Metashape© Professional Edition v1.8.4. Results of the modelling are discussed in 'Initial results'. Details of the photography are included in Table 1.

After the sites were successfully modelled, two alternative processes for applying a DStretch-enhanced texture to the model were explored. All DStretch enhancement was completed using ImageJ© v1.53t with the DStretch plugin v8.41 installed. The first of these processes relies on the batch process mode available within the DStretch plugin, which allows the same image enhancement settings to be applied consecutively to every image within a designated folder, exporting the enhanced images to a separate folder, thereby creating a complete new set of photographs which have the DStretch enhancement applied. This process is automated once started, requiring a few hours of processing to complete hundreds of high-resolution images. Within Agisoft Metashape, generating a new texture for an already produced model is possible by redesignating the file path used for the images used to generate the diffuse texture. Provided the dimensions and name of the images are identical, the existing alignment properties and UV maps created by Agisoft Metashape will be applied to the images in the redesignated file path. If the DStretch-enhanced images are renamed to be identical to their corre-

Site	Camera	Lens	ISO	Aperture	Shutter speed
Gulgurn Manya	Sony a7R iii	35 mm fixed focal length	400	f/6.3	1/80
Bunjil's Shelter	Sony a7R iii	35 mm fixed focal length	400	f/16	1/100

Table 1. *Camera settings used for image capture.*

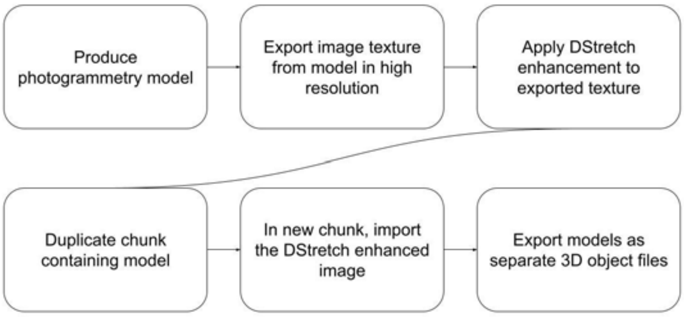

Table 2. *Flowchart of processing and enhancement workflow.*

sponding unenhanced source image, the new folder of DStretch-enhanced images can be used to generate a texture for the photogrammetry model.

This method would have the advantage of creating a complete batch of enhanced images in addition to the enhanced photogrammetry model texture. However, it was found that the batch mode offered within the DStretch plugin would not process images within the source folder consecutively, and as a result, re-arranged the order of images, thus preventing an easy option for batch renaming images in a simple consecutive naming convention. For this method to work, it would be necessary to move through each image individually and match each to the corresponding original image before manually renaming the enhanced image. Though possible, this would be a highly time-consuming process and introduce a high chance of error resulting from misidentifying the original images, producing warped and inaccurate photogrammetry textures.

The second method presents a significantly faster and simpler solution to generate DStretch-enhanced photogrammetry photomosaic images. Rather than applying enhancements to each image individually, DStretch enhancement can be applied to the diffuse texture (i.e. a generated photomosaic image representing the arrangement of colours on the model's surface) produced by Agisoft Metashape. After completing all modelling stages, the diffuse texture can be exported as a single image in various file formats, including TIFF or PNG, to prevent loss resulting from compression. This image texture can be enhanced using DStretch, exported and reimported as a new texture in Agisoft Metashape. The enhanced image retains the generated UV mapping data produced for the original diffuse image, allowing the DStretch-enhanced texture to be identically projected onto the same coordinates on the 3D model, effectively producing an image enhancement of the entire model. This method is significantly faster and less prone to human and technical errors than the method previously described; however, it does have the disadvantage of relying on the colour accuracy of the generated photogrammetry texture. Although SfM photogrammetry can produce highly accurate diffuse textures, variations in lighting conditions across the site can cause Agisoft Metashape to blend images together, slightly distorting the colours — the same issue is not present with individual photographs. However, this method does not preclude the option to batch-process the images in DStretch separately. The Dstretch-enhanced 3D model can be used to identify and locate faded motifs, with the enhanced image inspected separately to confirm colour accuracy. Multiple DStretch enhancement pre-sets can be applied to the exported photomosaic and reimported into Agisoft Metashape, producing a selection of differently textured models to compare.

In order to display the models within a virtual reality head-mounted display (HMD), it is necessary to reduce the complexity of the models. High-detail photogrammetry models of large objects or sites typically comprise millions of polygons, requiring rendering power beyond the current capacity of most commercially available HMDs to display. The 'decimate' function within Agisoft Metashape allows for a significant reduction in the polygon count to more manageable levels. The textures can be transferred from the high-detail geometry models to the low-detail models, creating a less processing-intensive model that still retains the overall appearance of the original model, except when viewed very closely. Fine details that have been removed from the geometry of the decimated model can be imitated through the generation of normal maps. Normal maps visually imitate the fine detail appearance of complex geometry on relatively simple surfaces by procedurally simulating the interaction of light at each surface point. They allow for the appearance of complex geometry in 3D model viewers without the need for high-polygon counts and can be automatically generated within Agisoft Metashape for low-polygon decimated models using the high-polygon models as a reference. This allows for the appearance of detailed and realistic 3D models to be displayed by low processing power hardware, such as is found within most HMDs. High Dynamic Range Images (HDRIs) can be imported into 3D model viewing platforms to simulate real-world lighting conditions, generating a more realistic appearance than is achieved through standard flat and even lighting.

Initial results

The initial results of this pilot study were promising for future further-developed and complete virtual reality displays of rock art sites. The SfM photogrammetric modelling of the sites was successful, as was the DStretch enhancement of the exported photogrammetry textures and reapplication of the enhanced textures to the 3D models. The models were able to be optimised for viewing on low processing power hardware and were viewed in VR within a consumer-grade HMD (an Oculus© Quest 1), with minimal loss of detail through the inclusion of normal maps.

The photogrammetry model for Bunjil's Shelter was created using flash photographs. Image quality

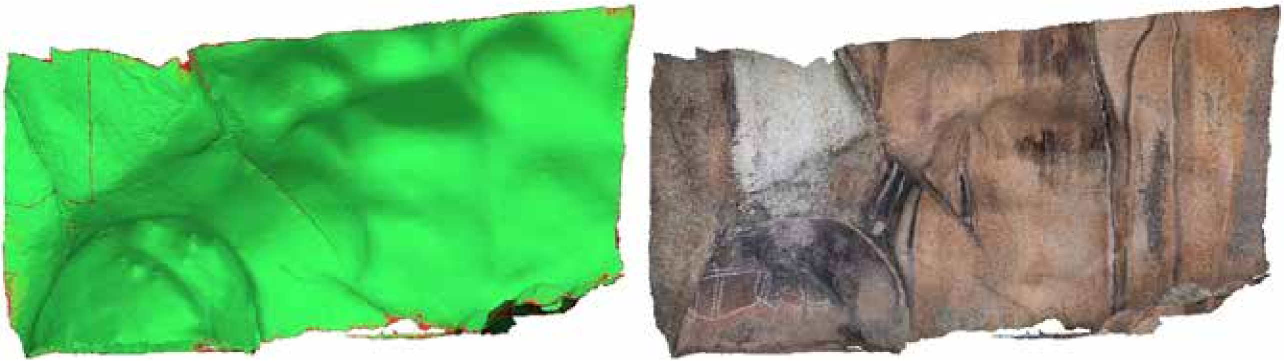

Figure 3. *Bunjil's Shelter model confidence and textured model. Red indicates low confidence, and green indicates moderate confidence.*

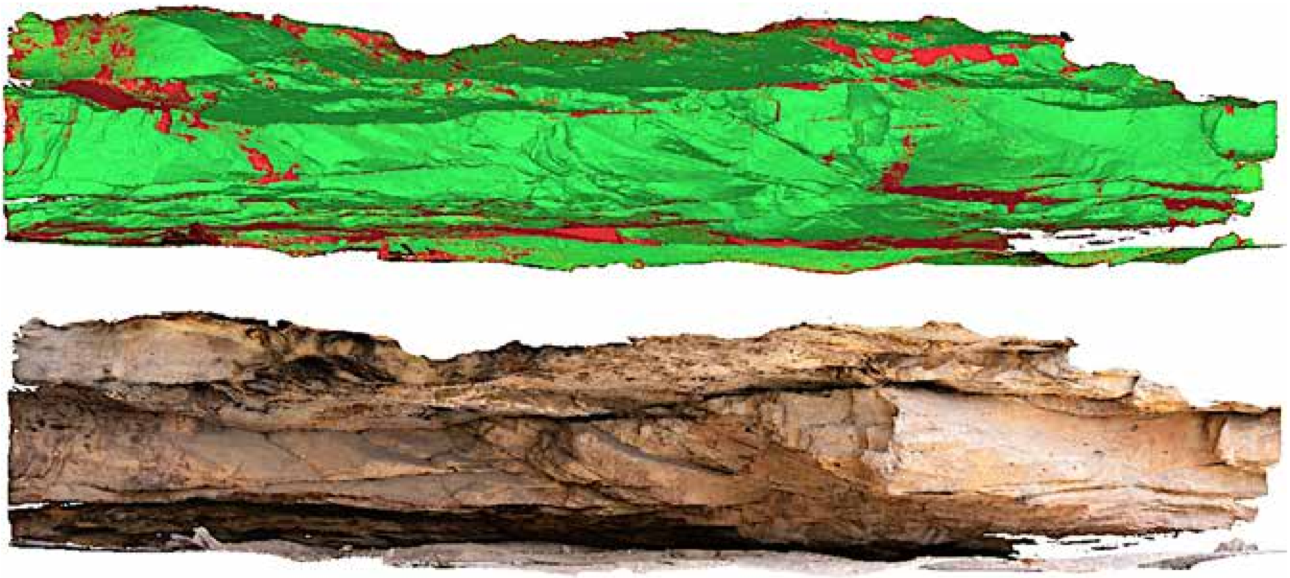

Figure 4. *Gulgurn Manya model confidence and textured model. Red indicates low confidence, and green indicates moderate confidence.*

was estimated within Agisoft Metashape to identify low-quality images that can be removed from processing. All images were above the recommended 0.5 quality threshold (Agisoft 2023: 25) and were successfully aligned. A model with approximately 7.9 million faces was produced after cropping extraneous regions. A ring flash was used during photography to even out the variation between lit areas and areas in shadow within the shelter. In order to avoid brightness variations, the default mosaic texture blending mode was used. A high degree of image overlap was obtained for the entirety of the site, with the majority of the model composed of >9 overlapping images. The model was overall of moderately high confidence (~5). There was a mean reprojection error of 1.06 pixels, indicating a high degree of accuracy. The final model and model confidence can be seen in Figure 3.

The photogrammetry model for Gulgurn Manya was created from daylight photographs, and so a longer exposure time and wider aperture were used to compensate for the lower available light than at Bunjil's Shelter. Image quality was again estimated within Agisoft Metashape, with those falling below the 0.5 quality threshold recommended by Agisoft Metashape excluded from further processing. All included images were successfully aligned, producing a model with just under 29 million faces after cropping. The model was overall of moderately high confidence (~5), with notable areas of low confidence in overhanging sections and crevices of the shelter, likely due to lower photographic coverage and low lighting. A high degree of image overlap was obtained, with the site ubiquitously covered with >9 overlapping images. There was a mean reprojection error of 2.15 pixels, likely a result of low confidence points below overhangs and within crevices. The final model and model confidence can be seen in Figure 4.

High-detail 16k textures (16 384 × 16 384 pixels) were generated for each model, exported and processed within ImageJ using the DStretch plugin. The different enhancement colour spaces were compared using the cycle function to visually identify which produced the most useful output. DStretch textures were produced for the LAB, CRGB, LBK, LDS and LRE colour space pre-sets, all at the default scale of 10. In both cases, the DStretch_lre10 colour space

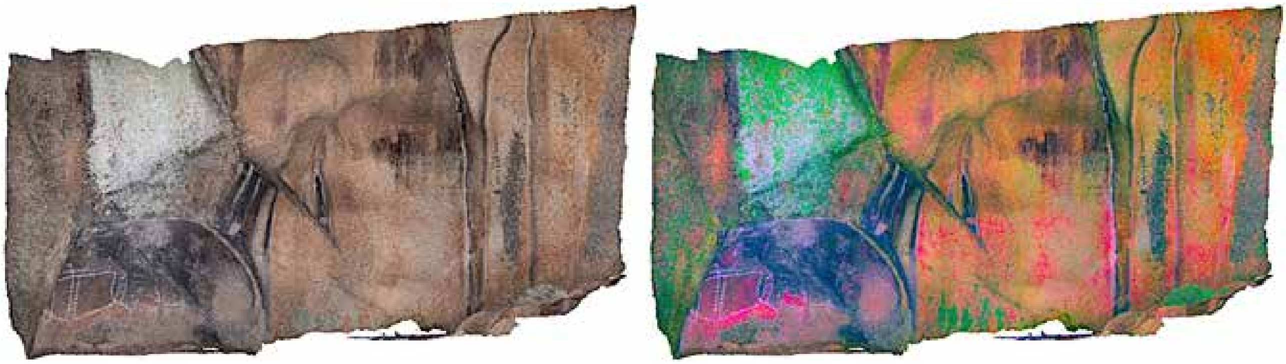

Figure 5. *Bunjil's Shelter textured model and with DStretch_lre10 texture applied.*

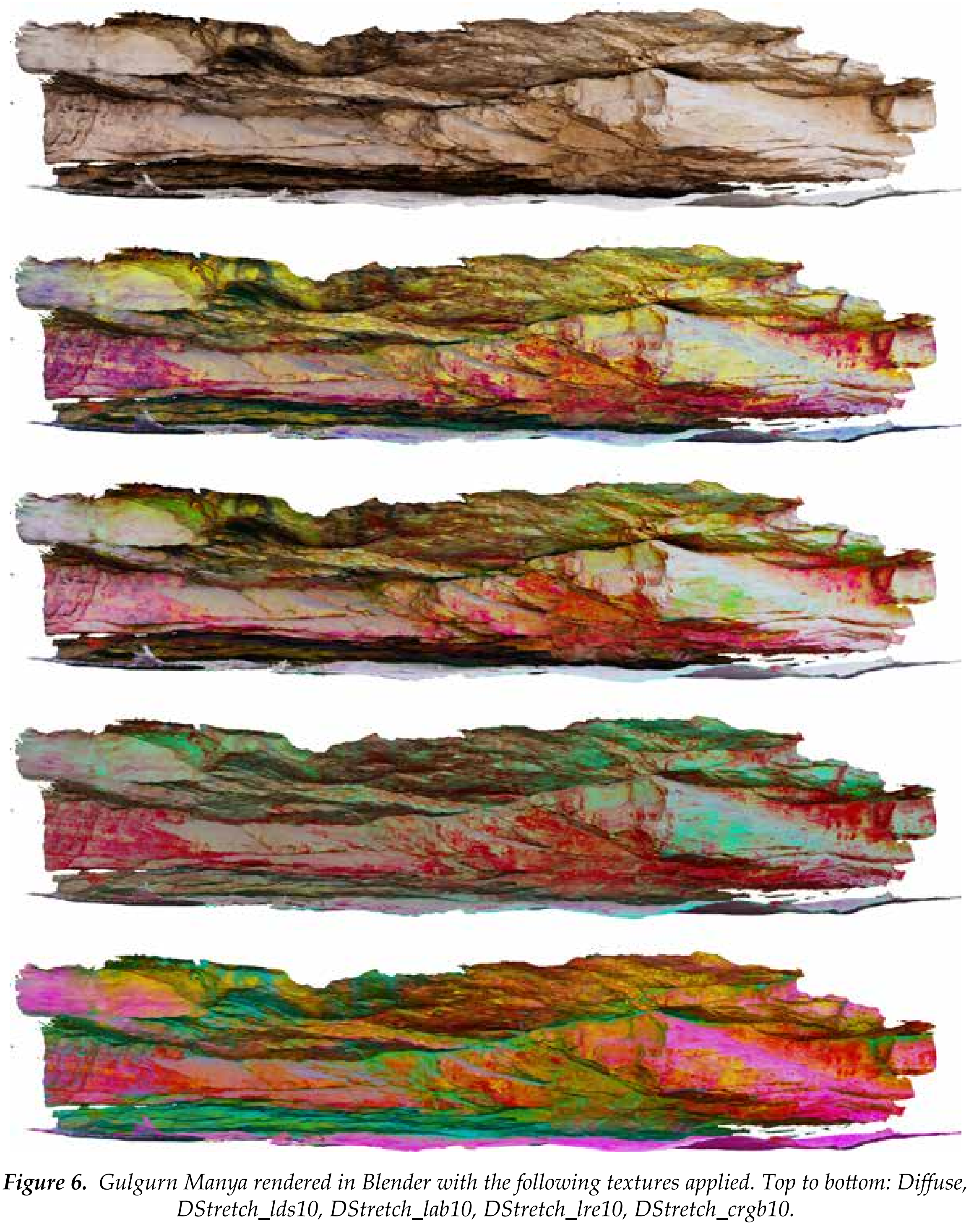

Figure 6. *Gulgurn Manya rendered in Blender with the following textures applied. Top to bottom: Diffuse, DStretch_lds10, DStretch_lab10, DStretch_lre10, DStretch_crgb10.*

transformation produced the most notable enhancement, particularly for Gulgurn Manya, given the prominence of red ochre. The models were duplicated within Agisoft Metashape, and the DStretch_lab10 textures were imported to texture the duplicated models. The newly textured models can now be exported in various 3D model formats, complete with the new texture (see Figs 5 and 6).

In order to view the models outside of Agisoft Metashape and on low processing power hardware, the size of both the models and textures needed to be reduced. Agisoft Metashape's decimate function was used to reduce models of both sites to a more manageable polygon count, and lower resolution 2k textures (2048 × 2048 pixels) were created from the original 16k textures. Reducing the visible amount of fine geometric detail lost was achieved by generating normal maps using the high-polygon model as a source. This process allows for low processing power hardware and online web hosting platforms to simulate the visual appearance of fine surface details under varying lighting conditions without the actual geometry. It also allows the models to be imported into other 3D modelling software packages, allowing for editing the models and greater control over lighting and camera angles. The decimated Gulgurn Manya model was imported into Blender© v2.93.3 with a variety of DStretch-derived textures applied, allowing users to cycle between them one by one, and generate rendered images (Fig. 6). Blender has the ability to easily move the rendering camera within 3D space, allowing these images to be generated from any angle of choosing (Fig. 7).

With the low-polygon decimated models and generated normal maps, the models require sufficiently little processing power that they can be hosted on web platforms, imported into video game engines, and viewed within virtual reality headsets rather than viewing them as simple rendered images. Davis et al. (2017) have earlier explored this possibility, importing photogram-

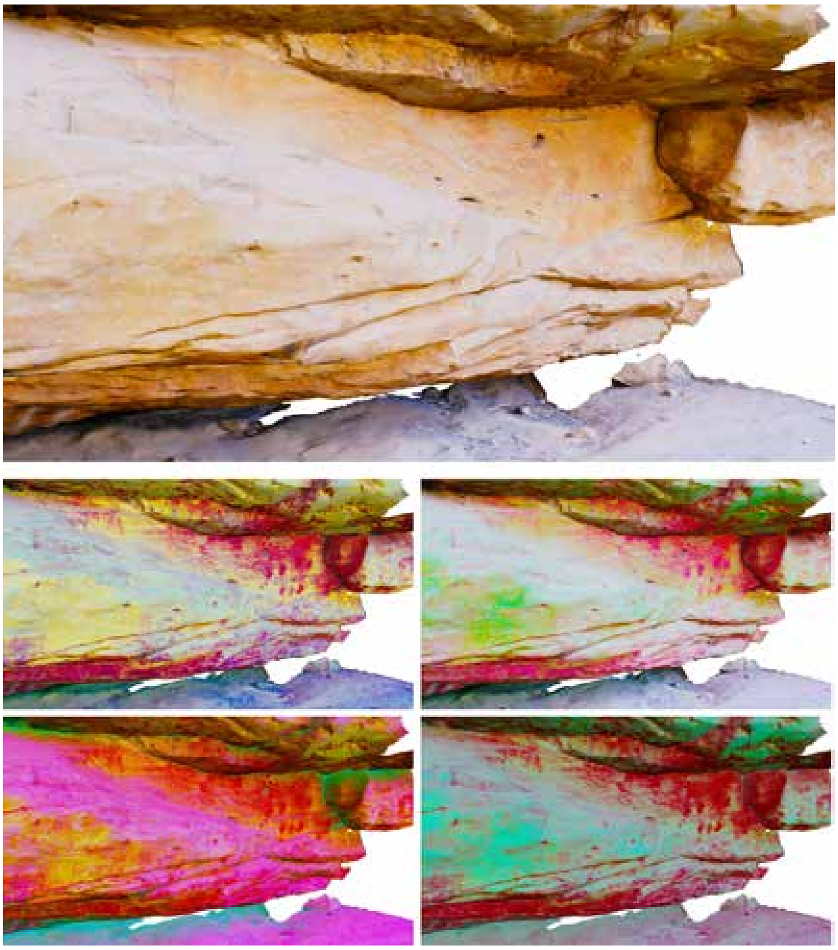

Figure 7. *Detail of the northern end of the Gulgurn Manya panel rendered in Blender with DStretch textures applied. Top: Diffuse (vibrance and saturation adjusted to emphasise prints). Bottom (clockwise from top left): DStretch_lds10, DStretch_lab10, DStretch_lre10, DStretch_crgb10.*

Figure 8. *Bunjil's Shelter model viewed within an Oculus head-mounted display via SketchFab's VR viewing function. The circle on the floor indicates where the controller is pointing in order to teleport around the model.*

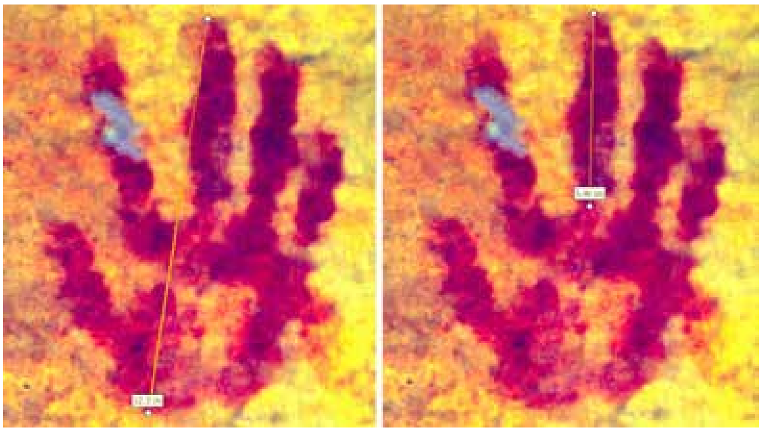

Figure 9. Measurements of Gulgurn Manya handprint taken from SfM photogrammetry model with imported DStretch_lds10 image texture. Hand length (left: 12.3 cm) and middle finger length (right: 5.96 cm).

metry models into the Unity game engine to allow Yinhawangka Traditional Owners to virtually explore the otherwise remote site, assisting with their management practices. Although video game engine platforms have made significant progress in recent years in developing user-friendly interfaces and many tutorials are now available online, developing within platforms such as Unity or the Unreal Engine still requires specialised skills outside the range of most researchers and archaeologists. However, these platforms are not necessary for viewing 3D models within HMDs. The online 3D model platform SketchFab© now has integrated VR viewing capabilities, only requiring models to be uploaded and some minor and intuitive settings adjusted within their 3D model settings. To test the capabilities, the model of Bunjil's Shelter was uploaded to SketchFab under a private domain accessible only by the author, which could be accessed through the web browser of an Oculus head-mounted display (Fig. 8). The same could be done for DStretch image textured versions of the model. This model was displayed informally at the 2023 Gariwerd Rock Art Management Forum.

Applications and discussion

Many researchers have noted photogrammetric modelling as a non-invasive, low cost and quick means of recording rock art sites in the interest of preservation, research and management (Blinkhorn 2015; Robinson et al. 2015; Bea and Angás 2017; Davis et al. 2017; Fernández-Lozano et al. 2017; Jalandoni and May 2020), as has the use of DStretch image enhancement (Harman 2005; Gunn et al. 2010, 2014; Domingo et al. 2015; Rodríguez González et al. 2019; Cabrelles et al. 2020; Andrews and Brink 2022). Either method, in isolation, has many useful applications, but combined they present unique opportunities for research, management and public engagement with rock art sites.

Photogrammetric modelling in isolation provides a means for spatial analysis and documentation that surpasses those offered through traditional field recording methodologies. When scaled and georeferenced, the models can be used to analyse the distance between identified motifs within and between sites or between motifs and work areas such as quarried surfaces or to take measurements of hand stencils and prints to estimate the age of the person who produced them (Fig. 9; Gunn 2006). Often, photogrammetry models are produced simply as a record of the site. While this alone has value, it is possible to extract more information from the models than is often noted in rock art literature.

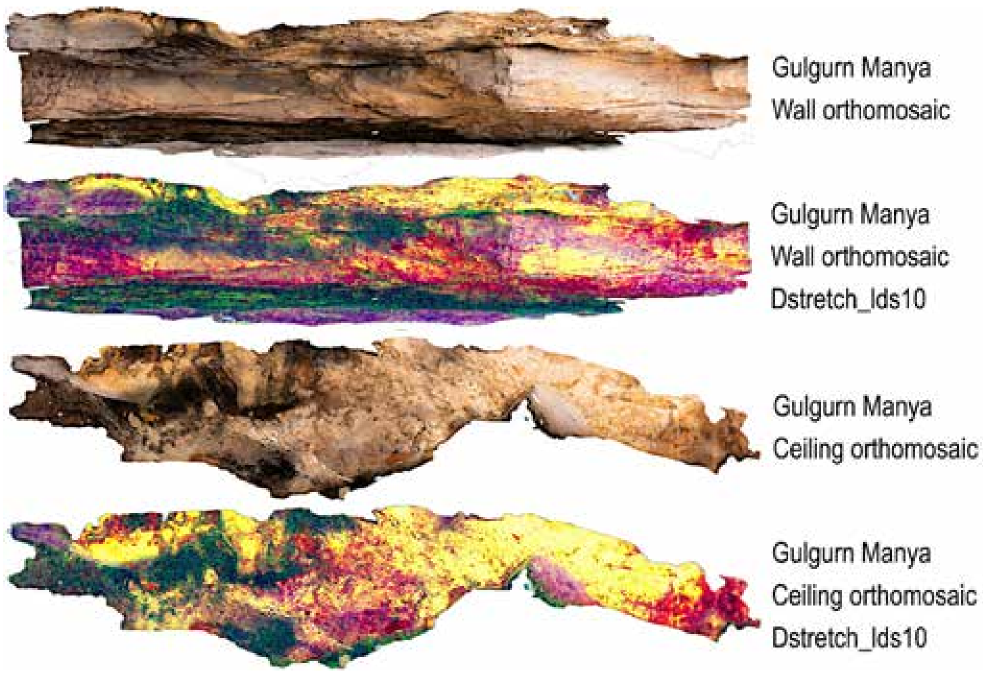

Figure 10. Top: Gulgurn Manya wall orthomosaics (original images 65 778 × 13 724 pixels) and ceiling orthomosaics (original images 65 968 × 14 434 pixels).

Orthomosaic generation allows for images to be created from any angle of choosing, producing a 'flat' orthorectified image of the site that would not be possible to capture using standard photography, as it can be generated from positions that would be physically impracticable in the field and is not subject to perspective warp caused by the camera lens. In the case of Gulgurn Manya, the shelter is now within a protective cage to prevent vandalism or accidental damage, making it impossible today to capture an unobstructed photograph of the entire expanse of the shelter. With the photogrammetry model, we are able to generate an image displaying the site without the cage in view, as the cage has been removed from the model (Fig. 10). The orthomosaic is correctly scaled and can be georeferenced, allowing it to be imported into GIS software for further analysis, and can be produced at a much higher resolution than could ever be obtained by a consumer-grade camera. For example, the Gulgurn Manya orthomosaic produced is at a resolution equivalent to an 860-megapixel photograph. By deleting portions of the model, it is also possible to generate orthomosaics of areas of the site that would typically be impossible to view from a single perspective, such as the ceiling or floor of a shelter. DStretch enhancement can also be applied to these orthomosaics to enhance motif clarity (Fig. 10).

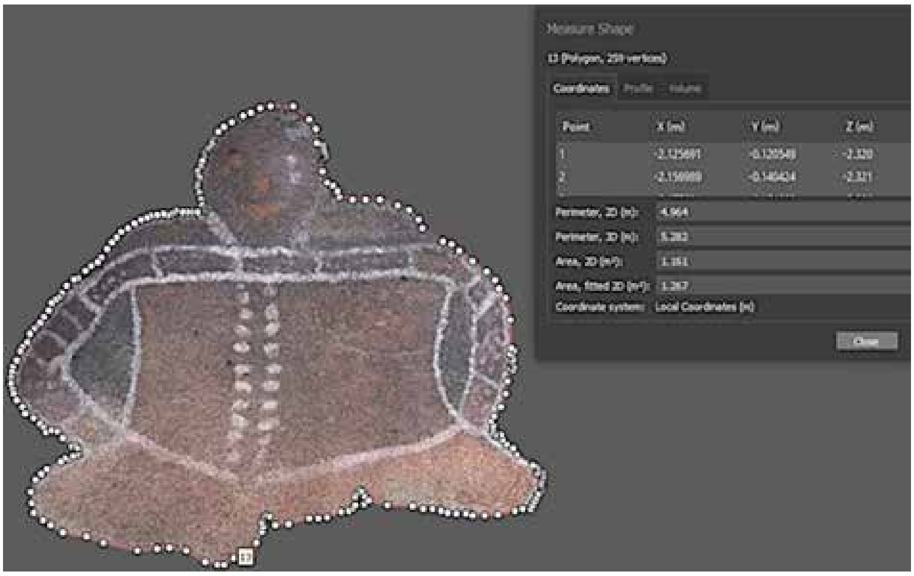

Figure 11. *Isolated panel of Bunjil with calculation of area within polygon.*

Using Agisoft Metashape's polygon feature, it is possible for motifs or features of the site to be accurately traced directly onto the model. A simple solution to recording from photogrammetry models is to draw a rectangular polygon capturing the entirety of the motif and recording the x and y dimensions (Jalandoni and May 2020). For denser analysis, a more complex polygon containing many vertices can be traced around the borders. These shapes can be exported separately as shapefiles and imported into GIS software for recording and analysis, or they can be used within Agisoft Metashape to calculate the volume and perimeter of the enclosed area (Fig. 11). Polygons also allow traced motifs to be isolated and exported as individual 3D models or orthomosaics. This feature presents unique opportunities for the analysis and comparison of motifs. It could facilitate the calculation of the amount of ochre that was required to paint the panel or motif, allowing estimations of the production cost of rock art at a site to the painters and an analysis of the economic operative chains that supported the production (Fiore 2007).

When using the DStretch textured photogrammetry model, one can accurately trace faded motifs with unclear boundaries directly from the model. While tracing is possible using DStretch-enhanced photographs, tracing from the photogrammetry model allows for capturing the three-dimensional spatial and geolocational data of the motif to a high degree of accuracy, as SfM photogrammetry-derived orthomosaics have been found to be highly spatially accurate and suitable for archaeological 2D drawings (Korumaz and Yıldız 2021). The polygon traced onto the DStretch textured model will contain the same coordinates on the original model, allowing the complete motif to be isolated and exported as an individual model, even when portions of it are too faded to trace on the original (Fig. 12). These digital tracings onto the model are orthogonal to the motif and can be viewed from a variety of perspectives, eliminating the problem of paper tracing which necessarily flattens the image to a two-dimensional plane (Bea and Angás 2017: 163).

Virtual reality displays of rock art sites have previously been used to assist Traditional Owners with managing remote sites (Davis et al. 2017), create virtual restorations of rock art sites where panels have been removed (Bea and Angás 2017) and analyse remote sites (Cassidy et al. 2019). Outside of rock art sites, virtual reality has been widely used in heritage studies as a platform to engage general audiences (Matchar 2017), museum and heritage site visitors (Pujol-Tost and Economou 2007; Theodoropoulos and Antoninou 2022; Zhou et al. 2022) and students (Ibañez-Etxeberria et al. 2020; Coban et al. 2022) with displays of reconstructed archaeological sites. Virtual reality displays of heritage are noted for their unique ability to instil a sense of 'presence' in participants (Pujol-Tost 2017), allowing people to feel as though they are more directly interacting with the cultural material.

Given the cultural significance of rock art sites and their susceptibility to vandalism or degradation, virtual reality displays may offer an opportunity to allow people to virtually experience the site when access cannot or should not be granted in the interests of preservation or cultural sensitivity. Combining DStretch-enhanced textures with photogrammetry models could help to make these sites not only more

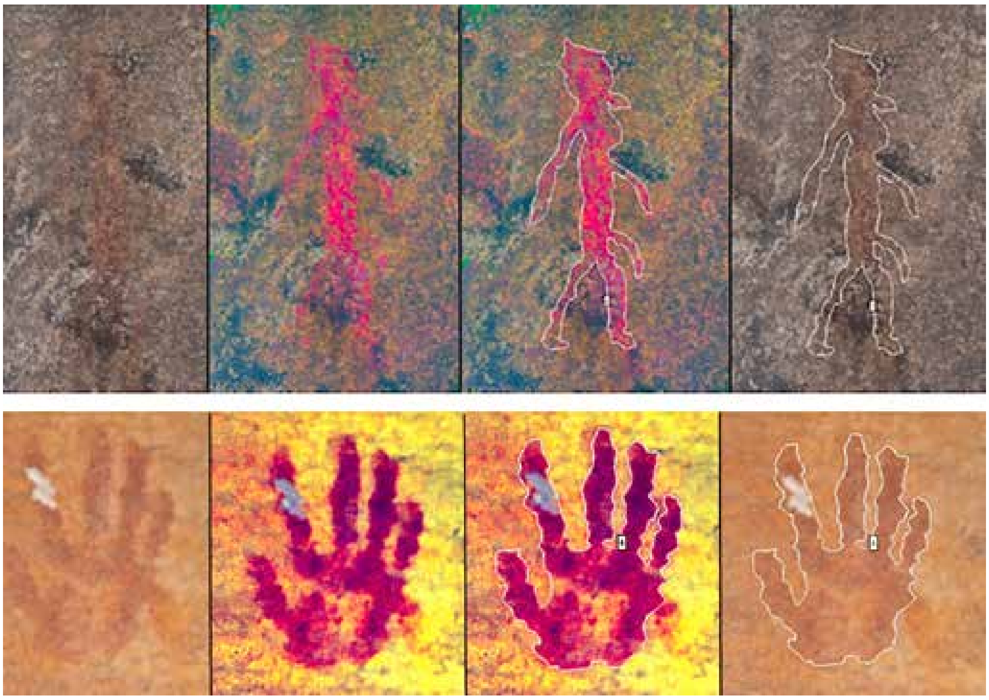

***Figure 12.** Top: motif from Bunjil's Shelter traced onto the DStretch_lre10 textured model, with polygon coordinates retained on the original model. Bottom: handprint from Gulgurn Manya traced onto the DStretch_lds10 textured model, with polygon coordinates retained on the original model.*

accessible but also more interpretable, highlighting otherwise faded motifs while also retaining the sense of presence that cannot be obtained through viewing still images alone. These displays can be easily distributed as digital files upon request or hosted online and accessed on a mobile phone using a QR code. Budget-friendly alternatives to true HMDs are readily available, with low-cost systems such as Google Cardboard or Samsung Gear VR allowing VR displays to be viewed on most new mobile phones. These systems could be sold or distributed at local cultural centres, allowing any visitor to view the VR display on demand.

Future directions

This project, emerging from a serendipitous meeting at a rock art presentation in Melbourne, was only to be a pilot study designed to test whether combining DStretch image enhancement with photogrammetric modelling was possible and useful using readily available equipment. The findings demonstrated the possibility of the combination and suggested a wide range of further potential applications in analysis, management, education and public engagement. Following a presentation at the 2023 Gariwerd Rock Art Management Forum to gauge community feedback, attendees broadly supported the results.

With the implementation of a wider range of imaging techniques, a more sophisticated and detailed model could be created to add visual polish and finer resolution data. Only terrestrial photogrammetric modelling was used on these sites, and the range of the area captured was limited by accessibility. In the case of Bunjil's Shelter, only one portion of the site was modelled, creating an isolated and incomplete model that limits the level of spatial analysis possible and, when displayed in VR, may prevent viewers from the expected experience of reality. Although drone photography produces lower-resolution results, combining aerial photogrammetry of the surrounding area with terrestrial photogrammetry of the key panels would create a more complete and evocative virtual representation of the site. Although the models here were scaled using a scale bar, using a Total Station would allow for a more accurate and geolocated representation of the site.

Although photogrammetric modelling is a quick and efficient method for obtaining high-frequency spatial and visual data, it does have shortcomings that should be addressed if the project is developed further. Conventional SfM photogrammetry without specialised equipment cannot pick up the low frequency, fine resolution surface texture data, which plays a significant role in the visual impact of paintings. Other digital imaging methods, such as reflectance transformation imaging (RTI) and photometric stereo (PS), are much more capable of recording the fine surface details necessary to simulate the interaction of light on the painted surface accurately (Hasegawa et al. 2011). While RTI and PS are usually used in isolation, it is possible to combine the data obtained through these methods with photogrammetry data to produce a more realistic virtual representation of the site (Frank et al. 2021; Karami et al. 2022; Bornstein and Keep submitted).

While SketchFab© is a free, quick, and easy solution for making 3D models publicly available, its functionality remains limited. The online platform Pedestal 3D©, currently used by many universities across Australia, includes a range of features that facilitate users to undertake their own analyses of uploaded models, including the ability to take measurements, add comments, or create cross-sections (Rampe 2022), providing more educational potential. Similarly, while

SketchFab's integrated VR capabilities require very little technical knowledge, they are significantly limited when compared to displays developed through game engines such as Unity© or Unreal©. Notably, at present there is no ability to set collision boundaries on 3D models, allowing users to walk or teleport through surfaces, and participants unfamiliar with virtual reality or 3D models may not realise what has happened. When the model was displayed at the Gariwerd Rock Art Management Forum, at least one person accidentally viewed it from the reverse side, presenting a disorientating inverted mirror image of the intended model.

Developing a full display within a dedicated game engine would allow for a much more significant integration of a broad range of sensory data and contextual information. Virtual tour programs such as 3D Vista already offer interactive pop-up 'hotspot' functionality, allowing users to select floating icons to bring up video displays with audio narration, and have been explored as immersive options to present contextual data interactively (Trizio et al. 2019; Alberto et al. 2022; Keep 2022a; 2022b). However, at present, 3D Vista has limited movement, only allowing users to move between 360° stereoscopic images rather than navigate a true three-dimensional environment, having only three degrees of movement available (roll, pitch and yaw), rather than the full six degrees of freedom which include locational movement (Zikas et al. 2016). VR applications developed through game engines can include the full six degrees of freedom, providing a more immersive experience. Incorporating simulated environments using high dynamic range images (HDRIs) and ambient audio can additionally improve the perception of realism and presence. There is also significantly more potential for integrating interactive elements, contextual information and simple elements of gamification and storytelling, which have been demonstrated to increase engagement (Psomadaki et al. 2019; Škola et al. 2020) and learning (Coban et al. 2022; Zhou et al. 2022).

Conclusion

This pilot study demonstrated the ease with which photogrammetric modelling and DStretch image enhancement can be combined to create DStretch textured 3D models capable of being viewed within virtual reality applications. This initial foray required a minimal investment in time and equipment yet was able to produce data that is of potentially unique use to Traditional Owners, archaeologists, and cultural heritage institutions. The DStretch textured models were able to generate orthorectified images with scaling, facilitate the digital tracing of motifs, calculate the volume of isolated motifs and be displayed within virtual reality applications. With additional work, there is potential to create more immersive and engaging virtual representations of these rock art sites, which could be of potential use in assisting Traditional Owners with the ongoing management of these sites, archaeologists and Traditional Owners with researching and analysing the sites, cultural institutions with engaging and informing the public, and educational institutions with teaching aids.

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REFERENCES

Agisoft 2023. *Agisoft Metashape user manual: Professional Edition, version 2.0*. Agisoft LLC.

Alberto, U., B. Alessia, M. C. Gatto and A. Curci 2022. The site of Nag El-Hamdulab in 360°: an alternative way to experience a story from the past. In M. Carrero-Pazos, R. Döhl and J. J. van Ransburd (eds), *Rock art research in the digital era*, pp. 135–148. BAR Publishing, Oxford.

Andrews, T. D. and J. W. Brink 2022. Using RetroReveal as a complement to DStretch for enhancing red ochre pictographs. *Canadian Journal of Archaeology* 46(1): 1–15; doi:10.51270/46.1.1.

Bea, M. and J. Angás 2017. Geometric documentation and virtual restoration of the rock art removed in Aragón (Spain). *Journal of Archaeological Science: Reports* 11(Feb.): 159–68; doi:10.1016/j.jasrep.2016.11.025.

Bekele, M. K., R. Pierdicca, E. Frontoni, E. S. Malinverni and J. Gain 2018. A survey of augmented, virtual, and mixed reality for cultural heritage. *Journal on Computing and Cultural Heritage* 11(2): 1–36; doi:10.1145/3145534.

Blinkhorn, J. 2015. The digital future of prehistoric rock art in India. *Visual Culture in the Indian Subcontinent* 5(1): 22–32.

Bornstein, D. and T. J. Keep [submitted for publication]. New dimensions in conservation imaging: combining photogrammetry and photometric stereo for 3D documentation of heritage artefacts.

Cabrelles, M., J. L. Lerma and V. Villaverde 2020. Macro photogrammetry & surface features extraction for Paleolithic portable art documentation. *Applied Sciences* 10(19): 690; doi:10.3390/app10196908.

Cassidy, B., G. Sim, D. W. Robinson and D. Gandy 2019. A virtual reality platform for analyzing remote archaeological sites. *Interacting with Computers* 31(2): 167–176; doi:10.1093/iwc/iwz011.

Chandler, J. H., J. G. Fryer and H. T. Kniest 2005. Non-invasive three-dimensional recording of Aboriginal rock art using cost-effective digital photogrammetry. *Rock Art Research* 22(2): 119–130.

Chang, H.-Y., T. Binali, J.-C. Liang, G.-L. Chiou, K.-H. Cheng, S. W.-Y. Lee and C.-C. Tsai 2022. Ten years of augmented reality in education: a meta-analysis of (quasi-) experimental studies to investigate the impact. *Computers & Education* 191(Dec.): 104641; doi:10.1016/j.compedu.2022.104641.

Christofi, M., C. Kyrlitsias, D. Michael-Grigoriou, Z. Anastasiadou, M. Michaelidou, I. Papamichael and K. Pieri 2018. A tour in the archaeological site of Choirokoitia using virtual reality: a learning performance and interest generation assessment. In M. Ioannides, J. Martins, R. Žarnić and L. Veranika (eds), *Advances in digital cultural heritage*, pp. 208–217. Springer, Cham.

Clark, I. D. 2002. Rock art sites in Victoria, Australia: a management history framework. *Tourism Management* 23: 455–464; doi:10.3316/informit.159341928235589.

Clark, I. D. 2017. Bunyip, Bunjil and mother-in-law avoidance: new insights into the interpretation of Bunjils Shelter, Victoria, Australia. *Rock Art Research* 34(2): 189–92; doi:10.3316/informit.159341928235589.

Coban, M., Y. I. Bolat and I. Goksu 2022. The potential of immersive virtual reality to enhance learning: a meta-analysis. *Educational Research Review* 36(June): 100452; doi:10.1016/j.edurev.2022.100452.

Davis, A., D. Belton, P. Helmholz, P. Bourke and J. McDonald 2017. Pilbara rock art: laser scanning, photogrammetry and 3D photographic reconstruction as heritage management tools. *Heritage Science* 5(1): 1–16.

Domingo, I., B. Carrión, S. Blanco and J. L. Lerma 2015. Evaluating conventional and advanced visible image enhancement solutions to produce digital tracings at El Carche Rock Art Shelter. *Digital Applications in Archaeology and Cultural Heritage* 2(2–3): 79–88; doi:10.1016/j.daach.2015.01.001.

Economou, M. and L. Pujol-Tost 2008. Educational tool or expensive toy? Evaluating VR evaluation and its relevance for virtual heritage. In Y. Kalay, T. Kvan and J. Affleck (eds), *New heritage: new media and cultural heritage*, pp. 242–260. Routledge, London.

Fernández-Lozano, J., G. Gutiérrez-Alonso, M. Á. Ruiz-Tejada and M. Criado-Valdés 2017. 3D digital documentation and image enhancement integration into schematic rock art analysis and preservation: the Castrocontrigo Neolithic rock art (NW Spain). *Journal of Cultural Heritage* 26(July): 160–166; doi:10.1016/j.culher.2017.01.008.

Fiore, D. 2007. The economic side of rock art: concepts on the production of visual images. *Rock Art Research* 24(2): 149–160.

Fraile, F. J. L., L. M. G. García and A. C. Klink 2016. 3D documentation and use of DStretch for two new sites with post-Palaeolithic rock art in Sierra Morena, Spain. *Rock Art Research* 33(2): 127–142.

Frank, E., S. Heath and C. Stein 2021. Integration of photogrammetry, reflectance transformation imaging (RTI), and multiband imaging (MBI) for visualization, documentation, and analysis of archaeological and related materials. *ISAW Papers*; http://hdl.handle.net/2333.1/0cfxq0c3.

Gard, S., S. Bucolo and T. G. Wyeld 2005. Capturing Australian indigenous perception of the landscape: virtual environments with cultural meanings. In H. Thwaites (ed.), *Proceedings of the 11th International Conference on Virtual Systems and Multimedia, Ghent, Belgium*, pp. 1–5. Archaeolingua, Gent.

Gunn, R. G. 1995. Guidelines for recording Australian Aboriginal rock imagery. In G. K. Ward and L. A. Ward (eds), *Management of rock imagery*, pp. 124–127. Occasional AURA Publication 9, Australian Rock Art Research Association, Melbourne.

Gunn, R. G. 2006. Hand sizes in rock art: interpreting the measurements of hand stencils and prints. *Rock Art Research* 23(1): 97–112.

Gunn, R. G., L. C. Douglas and R. L. Whear 2014. Interpreting polychrome paintings using DStretch. *Rock Art Research* 31(1): 101–104.

Gunn, R. G., C. L. Ogleby, D. Lee and R. L. Whear 2010. A method to visually rationalise superimposed pigment motifs. *Rock Art Research* 27(2): 131–136.

Harman, J. 2005. Using decorrelation stretch to enhance rock art images. *http://www.dstretch.com/AlgorithmDescription.html.* Paper originally presented at American Rock Art Research Association Annual Meeting 2005.

Hasegawa, T., N. Tsumura, T. Nakaguchi and K. Iino 2011. Photometric approach to surface reconstruction of artist paintings. *Journal of Electronic Imaging* 20(1): 013006-1–11; doi:https://doi.org/10.1117/1.3533329.

Howitt, A. W. 1904. *The native tribes of South Eastern Australia*. MacMillan, London.

Ibañez-Etxeberria, A., C. J. Gómez-Carrasco, O. Fontal and S. García-Ceballos 2020. Virtual environments and augmented reality applied to heritage education. An evaluative study. *Applied Sciences* 10(7): 2352.

Jalandoni, A. and S. K. May 2020. How 3D models (photogrammetry) of rock art can improve recording veracity: a case study from Kakadu National Park, Australia. *Australian Archaeology* 86(2): 137–46; doi:10.1080/03122417.2020.1769005.

Karami, A., F. Menna and F. Remondino 2022. Combining photogrammetry and photometric stereo to achieve precise and complete 3D reconstruction. *Sensors* 22(21): 8172-1–24; doi:10.3390/s22218172.

Katifori, A., M. Roussou, S. Perry, P. Cignoni, L. Malomo, G. Palma, G. Drettakis and S. Vizcay 2019. The EMOTIVE Project - Emotive Virtual Cultural Experiences through Personalized Storytelling (Nov.); doi:10.5281/ZENODO.3554475. https://zenodo.org/record/3554475.

Keep, T. J. 2022a. The Mernda VR Project: bringing rural Australian heritage into the digital era. *Excavations, Surveys and Heritage Management in Victoria* 11: 83–98; doi:https://doi.org/10.26181/21846045.v1.

Keep, T. J. 2022b. The Mernda VR Project: the creation of a VR reconstruction of an Australian heritage site. *Journal of Computer Applications in Archaeology* 5(1): 238–54; doi:http://doi.org/10.5334/jcaa.91.

Korumaz, S. A. G. and F. Yildiz. 2021. Positional accuracy assessment of digital orthophoto based on UAV images: an experience on an archaeological area. *Heritage* 4(3): 1304–27; doi:10.3390/heritage4030071.

Lacko, J. 2019. Cultural heritage objects in education by virtual and augmented reality. In M. Claudia, T. Dieck and T. Jung (eds), *Augmented reality and virtual reality*, pp. 175–187. Springer International Publishing, Chiam; doi:10.1007/978-3-030-06246-0_13. http://link.springer.com/10.1007/978-3-030-06246-0_13.

Lennon, J. 2011. Beyond the pale: the plight of remote area heritage. *Historic Environment* 23(2): 26–32.

Loendorf, L. 2001. Rock art recording. In D. S. Whitley (ed.), *Handbook of rock art research*, pp. 55–79. Altamira Press, Walnut Creek.

Massola, A. 1956. Aboriginal paintings at the Flat Rock shelter. *Victorian Naturalist* 73: 21–23.

Massola, A. 1957. Bunjil's cave found. *Victorian Naturalist* 74: 19–22.

Matchar, E. 2017. See the ancient world through virtual reality. *Smithsonian Magazine* (Feb.); https://www.smithsonianmag.com/innovation/see-ancient-world-through-virtual-reality-180962237/.

Merchant, Z., E.T. Goetz, L. Cifuentes, W. Keeney-Kennicutt and T. J. Davis 2014. Effectiveness of virtual reality-based instruction on students' learning outcomes in K-12 and higher education: a meta-analysis. *Computers &*

Education 70: 29–40; doi:10.1016/j.compedu.2013.07.033.

Ogleby, C. 1995. Digital technology in the documentation and management of rock art. In A. Thorn and J. Brunet (eds), *Preservation of rock art*, pp: 80–87. Occasional AURA Publication 9. Australian Rock Art Research Association, Melbourne.

Psomadaki, O. I., C. A. Dimoulas, G. M. Kalliris and G. Paschalidis 2019. Digital storytelling and audience engagement in cultural heritage management: a collaborative model based on the digital city of Thessaloniki. *Journal of Cultural Heritage* 36(March): 12–22; doi:10.1016/j.culher.2018.07.016.

Pujol-Tost, L. 2017. Cultural presence in virtual archaeology: an exploratory analysis of factors. *Presence: Teleoperators and Virtual Environments* 26(3): 247–263; doi:10.1162/pres_a_00296.

Pujol-Tost, L. and M. Economou 2007. Exploring the suitability of virtual reality interactivity for exhibitions through an integrated evaluation: the case of the Ename Museum. *Museology* 4: 81–97.

Rampe, M. 2022. Pedestal 3D features; *Pedestal3d*. https://pedestal3d.com/features/.

Robinson, D., M. J. Baker, C. Bedford, J. Perry, M. Wienhold, J. Bernard, D. Reeves, E. Kotoula, D. Gandy and J. Miles 2015. Methodological considerations of integrating portable digital technologies in the analysis and management of complex superimposed Californian pictographs: from spectroscopy and spectral imaging to 3-D scanning. *Digital Applications in Archaeology and Cultural Heritage* 2(2–3): 166–180; doi:10.1016/j.daach.2015.06.001.

Rodríguez González, E., S. C. Pastor and J. R. Casals 2019. Lost colours: photogrammetry, image analysis using the DStretch plugin, and 3-D modelling of post-firing painted pottery from the south west Iberian Peninsula. *Digital Applications in Archaeology and Cultural Heritage* 13(June): e00093; doi:10.1016/j.daach.2019.e00093.

Škola, F., S. Rizvić, M. Cozza, L. Barbieri, F. Bruno, D. Skarlatos and F. Liarokapis 2020. Virtual reality with 360-video storytelling in cultural heritage: study of presence, engagement, and immersion. *Sensors* 20: 5851; doi:10.3390/s20205851.

Smyth, R. B. 1878. *The Aborigines of Victoria* (2 vols). Government Printer, Melbourne.

Sullivan, S. 1983. Making a discovery: the finding and reporting of Aboriginal sites. In G. Connah (ed.), *Australian Archaeology: a guide to field techniques*, pp. 1–9. Australian Institute of Aboriginal Studies, Canberra.

Theodoropoulos, A. and A. Antoniou 2022. VR games in cultural heritage: a systematic review of the emerging fields of virtual reality and culture games. *Applied Sciences* 12(17): 8476; doi:10.3390/app12178476.

Trizio, I., F. Savini, A. Giannangeli, F. Marra, G. Fabbrocino and A. Ruggieri 2019. Versatile tools: digital survey and virtual reality for documentation, analysis and fruition of cultural heritage in seismic areas. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* 42: 377–384; doi:10.5194/isprs-archives-XLII-2-W17-377-2019.

Zhou, Y., J. Chen and M. Wang 2022. A meta-analytic review on incorporating virtual and augmented reality in museum learning. *Educational Research Review* 36(June): 100454; doi:10.1016/j.edurev.2022.100454.

Zikas, P., V. Bachlitzanakis, M. Papaefthymiou and G. Papagiannakis 2016. A mobile, AR inside-out positional tracking algorithm (MARIOPOT), suitable for modern, affordable cardboard-style VR HMDs. In M. Ioannides, E. Fink, A. Moropoulou, M. Hagedon-Saupe, A. Fresa, G. Liestøl, V. Rajcic and P. Grussenmeyer (eds), *Digital heritage. Progress in cultural heritage: documentation, preservation, and protection*, pp. 257–268. Springer, Cham.

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