Multi-image photogrammetry as a practical tool for cultural heritage survey and community engagement

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A B S T R A C T

Multi-image photogrammetry is rapidly emerging as an important archaeological tool due in large part to the increasing level of automation in off the shelf software. The technique can offer significant reductions in the cost of archaeological survey and in the enhancement of survey results and is of particular value therefore to archaeologists working in contract-led context, which in many areas accounts for the majority of archaeological work (up to 80% in Scotland for example). Recent advances in multi-image photogrammetric software have resulted in highly automated workflows and significantly reduced the burden of technical knowledge required to produce survey results of an acceptable standard. Although the majority of multi-image photogrammetry surveys are still undertaken in an academic context the technique is increasingly being used by a far wider proportion of heritage professionals, many of whom are not first and foremost specialists in photogrammetry. The adoption of such highly automated workflows presents certain risks with regard to accuracy and reliability of results as noted by Remondino et al. (2012, 52). However the enormous potential of the technique for rapid and accurate survey and for reduced costs cannot be ignored and the challenge we face is to ensure that the highly automated workflows adopted by archaeologists in contract-led contexts are robust and reliable and underpinned by guidance and knowledge exchange. This paper is not intended as a comprehensive technical review of the technical aspects of the technique or of its development but instead focusses on highlighting its potential as a practical everyday tool for archaeological practitioners to apply in two of the main types of contract-led archaeological work, rapid survey and community engagement. A non-technical overview of the technique is given followed by case studies illustrating how the technique has been applied successfully in a non-academic contract-led and community engagement context. These surveys have been undertaken with very limited budgets for both survey and post-processing of data and typically with very limited time frames. In each case study, use of multi-image photogrammetry has allowed for better, faster and more cost-effective results than would otherwise have been possible. Case studies include a survey of an Iron Age fort, a rapid survey of exposed segments of an intertidal wreck, both commissioned for heritage management purposes and a community survey of a 17th century gravestone undertaken by children under the age of 16. Finally the obstacles to wider adoption in the contract-led sector are discussed and it is argued that a concerted approach is required to create and disseminate simple and reliable workflows.

1. Introduction

Multi-image photogrammetry or Structure from Motion is a relatively new technique for accurate digital capture of 3-dimensional objects and surfaces. The technique is practical and versatile and is increasingly being adopted for cultural heritage to replace or enhance more established survey techniques such as manual survey and laser scanning. In multi-image photogrammetry, some of the most technically challenging and time-consuming elements of traditional stereo and convergent photogrammetry have now been automated and it is now possible to combine large groups of images rather than pairs, making this a far more cost-effective, user-friendly and powerful approach. As a result there is an increasing number of published examples of archaeological surveys based wholly or partly on recording of 3-dimensional features using multi-image photogrammetry. The vast majority of these have been undertaken in academic or research contexts despite the fact that in many areas the bulk of
archaeological survey and excavation, is undertaken by archaeologists in commercial or non-profit heritage organisations funded through contracted heritage projects, much of which can be characterised as pre-development mitigation survey and excavation. The slower adoption of the technique in this sector is due to the amount of time and technical expertise required to achieve accurate results, archaeologists working in commercial contexts having relatively little time to devote to research and development. Working under contractual obligations to produce results to a predefined standard can also discourage innovative or experimental methodologies which carry a higher risk of failure. As with the early days of laser scanning there is a need for collaboration and skill sharing across the entire heritage sector in order to realise the full potential of multi-image photogrammetry. Of particular interest, given the simplicity of the photogrammetric data capture, is the potential for use of multi-image photogrammetry as a tool for community outreach and engagement projects, an increasingly important part of the contract-led heritage sector.

As recently as 2003 an assessment of the value of multi-image photogrammetry for recording of carved stones in Scotland found the technique to be unsuitable for detailed recording of archaeological features, due mainly to the low level of detail in the models that could be generated within a reasonable amount of time. However due to subsequent improvements in software, the technique has undergone a rapid evolution, making it much more useful and accessible than ever before. As a result of these developments it can now be said with confidence that under certain conditions, multi-image photogrammetry offers archaeologists a viable alternative in terms of technical complexity, accuracy, cost and flexibility to established techniques such as manual survey and laser scanning. The wider adoption of the technique is being driven by an on-going convergence of related technologies, including advances in digital photography, in the development of reliable Small Unmanned Aircraft (SUA) such as quadcopters and hexacopters, in more efficient and powerful software and by increasing computing power both on desktops and in the cloud. A number of surveys undertaken by the author in the UK in 2012 using this technique are presented in order to illustrate the value of multi-image photogrammetry as a practical and cost-effective method for accurate survey and as a tool for community engagement with heritage.

2. Defining photogrammetry

As stated above the contract-led heritage sector has been conservative in its use of multi-image photogrammetry and given that one of the aims of this paper is to encourage the adoption of the technique by archaeologists with limited or no experience of the technique, it is appropriate to give a brief overview of the technique and its application in heritage. For a more comprehensive and technical discussion see Szeliski (2011).

In simple terms, photogrammetry is the process of making measurements of features through analysis of overlapping photographs, and is fundamentally based on trignometry. As early as the 1850s a French Army surveyor, Aimé Laussedat, realised that where the optical characteristics of a camera are known, multiple images taken with that camera from slightly different angles could be compared to obtain accurate measurements of the relative dimensions of that subject (Laussedat, 1854, 1859). Laussedat successfully applied the technique to ground-level topographical survey. However, the equipment available meant that great technical skill and extensive manual calculation were required. Adoption of photogrammetric techniques was gradual and limited and theodolites have remained the main tool for ground-based survey to the present day. Since Laussedat’s time the most successful application of the technique has been for large scale aerial survey of topography by cartographers such as the Ordnance Survey of Great Britain. This approach relies on overlapping vertical aerial photographs analysed using various techniques such as stereo plotters. Because of the scale of the area covered this was one of the few applications of photogrammetry where the amount of time required for the technique was outweighed by the benefits derived from it. In the last decades of the 20th century a significant effort was made to automate as much as possible of the workflow in order to reduce the burden of analysis. However it was not until the advent of digital photogrammetry in the early 1990’s, where film was replaced by scanned digital surrogates, optical trains replaced by computers and left/right eye-pieces with 3D monitors, that automation in photogrammetry really took off allowing 3D data to be automatically generated using pixel correlation algorithms. Despite this the technique remained a highly specialised and expensive technique, both in terms of time and hardware.

3. Archaeological applications of stereo photogrammetry

One of the main applications of photogrammetry for a specifically archaeological purpose has historically been analysis of stereo aerial photography for accurate aerial mapping of archaeological features such as crop marks. Despite the need for extensive manual input, a number of attempts have also been made by archaeologists to apply stereo photogrammetry to terrestrial survey. One of the most notable recent heritage photogrammetric surveys was a pioneering survey at Stonehenge, resulting in the creation of 350 digital models of the megaliths (Bryan and Clowes, 1997). However, as Jeffrey (2003) points out, due extensive manual editing required the surveyors did not attempt to model fine surface detail such as faint carvings on the stone but to aim for a point density of two centimetres in order to capture an accurate geometric model of the stones. Even so the processing ran for over three years. Another more recent example of photogrammetry based on stereo pairs was the highly successful Northumberland and Durham Rock Art Project (NADRAP), an English Heritage-funded project led by Northumberland and Durham County Councils (Bryan and Chandler, 2008). A total of around 1500 rock art sites were recorded using stereo photogrammetry with a high degree of success, producing dense and accurate 3D models of the features. The project relied heavily on volunteers, both for data capture and processing. However, there were a number of limiting factors encountered. Although the workflow adopted was relatively simple, it relied on proprietary software and was limited to stereo-pairs captured with pre-calibrated cameras. The cameras were calibrated for a specified distance from the subject, thus limiting the size of area that could be captured (Bryan and Chandler, 2007, 213). Capture of larger rock art panels required multiple stereo-pair models to be combined. However this proved to be too time-consuming and the majority of sites were recorded using stereo photogrammetry only. Despite the success of these projects, it is clear that stereo photogrammetry has been restricted to a very small and specialised proportion of the archaeological community.

4. Defining multi-image photogrammetry

The term ‘Multi-image Photogrammetry’ (sometimes used interchangeably with ‘Structure from Motion’) is used in this paper to describe to a more recently developed approach to photogrammetry, where stereo pairs are no longer the focus. Instead much larger datasets of overlapping digital images of a feature taken from different positions can be loaded in a single batch into software capable of automatic camera calibration, feature matching and reconstruction of complex dense 3-Dimensional models, with
minimal manual input. With the right combination of hardware and software, multi-image photogrammetry can produce highly detailed and accurate models of both topography and discrete objects or monuments. As it is not limited to stereo pairs it is also capable of modelling more complex objects and it is not necessary to maintain a known distance from the subject.

There has been an explosion in the range of multi-image photogrammetry software packages available in the last decade with an attendant improvement in automation and interface. Current software packages range from free open-source programs to professional-grade packages costing thousands of pounds. Many of these have been released or significantly updated within the last three years. In this paper three software packages have been discussed. These are VisualSfM (by Changchang Wu and others), 123D Catch (by Autodesk) and PhotoScan (by Agisoft). These surveys were undertaken separately and do not constitute a direct comparison of the various workflows although they do demonstrate a range of open source, commercial and cloud-based techniques, varying greatly in the level of technical knowledge and input required. For an excellent comparative analysis of some of the capabilities of some of the main software packages using a single dataset see Remondino et al. (2012). Archaeologists have been quick to adopt the technology for a variety of purposes and it is sufficient to highlight some recent examples. It has been applied to archaeological excavation in Belgium by the University of Ghent (De Reu et al., 2013; De Reu et al., 2014) and in Israel by the Tell Akko Project (Pennsylvania State University, the University of Haifa and others) (Olson et al., 2013). Recent examples of aerial multi-image photogrammetry include projects by the University of Ghent in Belgium (Verhoeven, 2011) and Italy (Verhoeven et al., 2012). Rock art recording has been undertaken by the University of Ghent in Siberia (Plets et al., 2012a,b) and the universities of Loughborough and Newcastle in Australia (Chandler et al., 2005). Artefact recording has been undertaken by the Institute for Language and Speech Processing and the University of Ljubljana (Koutsoudis et al., 2013) and the University of Haifa (Gilboa et al., 2013). Examples of applications for recording of buildings include studies undertaken by Parma University at Italian sites (Roncella et al., 2011). These few examples should serve to illustrate that much of this work has been undertaken in an academic context.

5. How multi-image photogrammetry works

As discussed above there are numerous publications which have described in technical detail single software packages and workflows and a smaller number which attempt direct comparisons but given the relative novelty of the technology a generic and non-technical description is given below. Regardless of which software package has been chosen, the transformation of 2D digital images into 3D digital models is generally carried out in a similar way.

The first step is to acquire a set of images of the subject of interest. These images must have a large amount of overlap with each part of the surface to be modelled visible in at least three images. Almost any camera can be used although better results are more likely with a high end camera such as an SLR. For optimal results the settings of the camera (particularly zoom) should not be changed during the data capture. Choosing a subject which is not moving is also crucial as moving elements will impair the ability of the software to successfully match features between images. In multi-image photogrammetry it is not necessary to record each camera location as this can be calculated from the images themselves and this is undoubtedly one of the greatest advantages of the technique. Control points may be used if desired to tie the model into a known coordinate system and to provide a scale for the final model.

The second step is to load the images into the software for analysis and automatic detection of matching correlated features at various scales between images. Many of the multi-image photogrammetry packages currently available use an algorithm known as Scale-Invariant Feature Transform or SIFT (Lowe, 1999) which can match features despite changes in the scale or orientation of the images. Because multi-image photogrammetry software can analyse large numbers of images, this stage can require a great deal of computer power and can be very time consuming. Each image must be compared to every other image and the number of comparisons necessary increases exponentially with each additional image. To deal with this issue some software packages are designed to upload images for processing in the cloud. In software such as Autodesk’s 123D Catch or Arc 3D which rely on remote computers the need for a local high-spec computer is bypassed but broadband internet access is required. Where image processing is undertaken locally it may be necessary to use a powerful computer, perhaps even one specifically designed to cope with photogrammetric datasets.

In the third step these matches between points are used to calculate the spatial relationship between them and in doing so, the relative positions of the cameras are indirectly derived from survey control applied within the orientation process. Each multi-image photogrammetry software package does this in a slightly different way but ultimately they all rely on trigonometry and iterative testing and refining of a model of both the surface of the subject and of the optical parameters of the camera. The end result of the second stage is a ‘sparse’ 3-Dimensional model which includes the relative camera locations and a small number of points on the subject or feature.

In the fourth step, using this ‘sparse’ 3D model, the software reanalyses the images and generates a much denser model of the subject. This takes the form of a point cloud similar to those generated by laser scanners. Unlike basic Terrestrial Laser Scanning (TLS) the attributes of the points in this model will always include colour values as they are derived from colour images. The maximum number of vertices in the output model is limited only by the number of pixels in the source images, the total number of those images and the capacity of the processing hardware. As there is no hard limit to the number of input images, there is theoretically no maximum size of point cloud and, given the high density of pixels in modern cameras, photogrammetric point clouds can be very dense. In practice the limiting factor is often computing power. Even where the system used has the capacity to process a model from hundreds of images, such large datasets may not be desirable as it might take days or even weeks to process them, particularly where standard consumer-grade computers are used. Problems can also arise where the resulting models are too large to work with, a problem familiar to archaeologists dealing with laser scans. The maximum number of points generated in a single model during testing by the author was just under a quarter of a billion points on a scan of a small carving less than 20 cm in diameter (Fig. 1). In this case it was found necessary to sub-sample the point cloud to provide a more workable dataset.

6. Case studies

One of the most attractive aspects of multi-image photogrammetry to contract-led archaeologists should be its applicability to almost every aspect of archaeological survey, from artefacts to landscapes. To illustrate this, three recent surveys led by the author are presented below. The first of these is a detailed survey of a promontory fort, commissioned by Forestry Commission Scotland and carried out by a professional team of surveyors from WA Heritage. This survey demonstrates how the technique can offer a cost-effective approach in a commercial context and a variety of
additional benefits. In this case photogrammetry was used to generate a series of detailed sections and plans and as an aid to interpretation of the phasing of the site. In the second example a much simpler workflow was used to model a pair of gravestones in a Scottish graveyard. In this case, image capture was carried out entirely by children between the ages of 10 and 16, all members of the Young Archaeologists’ Club (run by the Council for British Archaeology). This survey is used to illustrate the value of the technique for dissemination of archaeological features and for community engagement, an increasingly important area for contract-led archaeologists. In the final case study a survey of an intertidal wreck is used to illustrate how rapid recording using multi-image photogrammetry can be of use where time is a critical factor.

6.1. Survey at Rubha an Fhaing Dhuibh

In April 2012 Wessex Archaeology, a UK-wide heritage contractor, was commissioned by Forestry Commission Scotland to undertake a detailed archaeological measured survey of Rubha an Fhaing Dhuibh, a promontory fort of likely Iron Age date located on the southern bank of Loch Shiel, near Glenfinnan (NM 8130 7185). The aim of the survey was to inform conservation management plans for the monument and to provide an enhanced record of its current condition. The survey was undertaken over a period of three days (McCarthy, 2012). As a commissioned survey relying on professional archaeologists, cost was a major consideration when choosing a survey methodology. It was felt that the complex irregular nature of the stone banks across the site would take too long to survey manually using traditional techniques such as metre wide planning frames and the cost of laser scanning would be too high due to hardware overheads. In consultation with the FCS Archaeologist Matt Ritchie, it was decided to use the opportunity to test a multi-image photogrammetry workflow, testing the results against an outline Total station EDM survey.

The promontory itself lies at the edge of Loch Shiel, at the base of a large glacial valley and measures approximately 30 m in diameter. It was discovered only thirty years ago (Kirby, 1983) under dense vegetation. It faces on to the loch on its east, north and west sides and is connected to the shore on the south side at an area of marshy ground. The site is comprised of a jumble of boulders and rocks, many of which are arranged into recognisable walls including an enclosure divided into two cells, lying at the centre of the promontory. All around the loch edge the site is defined by a collapsed rubble bank running below the water line. Five short linear stone features of unknown purpose were observed radiating out from the rubble bank, in each case fully or partially located just below the water line. These stone lines or walls were all of a similar size and appear to be evenly spaced suggesting that they might be contemporary. They are of similar dry stone rubble construction built of stones around 30 cm in diameter and rest on the gravel loch floor. A more detailed description and interpretation of the site is given in an unpublished survey report (McCarthy, 2012) in the archives of the Royal Commission of Ancient and Historical Monuments of Scotland.

Much of the vegetation which had covered the site immediately prior to the survey was cleared in order to facilitate recording and interpretation. In order to establish a basic record of the site a Total Station survey was undertaken of the main upstanding features of the site and the outlines of rubble walls. Digital images were then gathered using a DSLR camera mounted on a 3 m long fibreglass pole. A rough grid was laid out across the site and vertical
exposures were taken at approximate half metre intervals. Each image covered an area of ground approximately 4 m in length by 3 m transversely and this allowed for a considerably greater overlap than the minimum required for photogrammetric modelling. This meant that it was not necessary to ensure the spacing between exposures was exact or even that the camera was exactly vertical. Oblique photos were also taken at various points around the site to provide additional coverage, particularly for vertical or overhanging surfaces. This approach resulted in over 2000 digital photographs which were successfully processed over the course of a week to generate a point cloud of over 40 million points using the multi-image photogrammetry software VisualSFM (Wu et al., 2011). Of particular importance, given the commercial nature of the project was the fact that this processing stage was almost entirely automated with minimal human intervention. VisualSFM is an open-source graphical user interface which bundles together several free programs including PMVS/CMVS (Furukawa and Ponce, 2010). 2-dimensional orthographic renders of the point cloud were then georeferenced in ArcGIS and used to create an accurate series of plans and elevations of the site including outlines of individual rocks which would have been impossible to capture in the same length of time using traditional methods (Figs. 2 and 3).

6.2. Survey at Aberlady

As a leader of the East Lothian branch of the Young Archaeologists’ Club of East Lothian, the author undertook a community-based photogrammetric survey. A Young Archaeologists’ Club
A simple multi-image photogrammetry workflow using 123D Catch by Autodesk was chosen. This software is user-friendly but offers minimal user control over processing. For example although 123D Catch generates a point cloud in order to create the final textured 3D mesh, it cannot be accessed or edited, making it impossible to remove erroneous points that may then reduce the fidelity of the final mesh. The software is therefore of limited value for survey in a professional context but its simplicity gives it several advantages for use in outreach and community engagement. Photogrammetric processing is undertaken on Autodesk's own servers rather than on a local computer and the software automatically generates visually appealing textured meshes and offers a simple interface for generating fly-through videos of models.

The subjects of the survey, chosen within the graveyard by the children themselves, were two gravestones, one of 19th century date and one of 17th century date, located at opposite ends of the graveyard. Only one hour was available for the survey including training. The group of five children (all under the age of 16) were given a ten minute talk on how to use digital cameras and how to take images suitable for photogrammetry (in this case by moving in a circle around the gravestones and relying on automatic settings for exposure). They were then split into two groups, one group using traditional hand-recording methods and one group recording using photogrammetry, in each case having around 20 min to undertake the recording, before switching techniques. The resulting photographs were loaded into 123D Catch by the author and processed overnight. They were presented to the children at the next meeting of the club in the form of a fly-through video and orthographic projections output using MeshLab, a 3D editing tool developed with the support of the 3D-CoForm project (http://www.3d-coform.eu/) and rendered with radiance scaling (Vergne et al., 2010) (Fig. 4). This shader helps to enhance minor variations in depth across a model (in some cases including detail that is not visible to the naked eye) (Granier et al., 2012). The fly-through video was also uploaded to the internet (http://www.youtube.com/watch?v=ZPxwC7mIToU). The results proved to be of excellent quality and it was noted that the surveys conducted through photogrammetry included far more detail than it had been possible for the children to record on the complex gravestones by hand, including capture of the feature’s colour, depth and volume. This survey is particularly relevant for contract-led archaeologists as it highlights how a simple multi-image photogrammetric workflow can facilitate 3-dimensional archaeological recording by members of the public with a minimum of training required to produce outputs that are not only accurate but which communicate the essence of the archaeological site in a highly accessible format. Given the increasing numbers of contract-led archaeologists working on community heritage projects there is a huge and largely untapped potential for multi-image photogrammetric projects incorporating volunteer survey.

Fig. 3. The accuracy of the point cloud was assessed through comparison with a series of 48 control points surveyed using a GNSS/Total Station System (Fig. 3). Despite the bracken cover a total of 37 of the 48 control points could be easily identified from the point cloud data. A horizontal accuracy analysis undertaken using a rasterised image of the point cloud exported from Cyclone was conducted in ArcGIS. Comparison of the two datasets gave a Root Mean Squared error of 3.634 cm when compared to the surveyed control points.
6.3. Tetney Sea line replacement

The speed of 3D data capture is one of the most attractive features of photogrammetric survey for contract-led archaeologists and this is well illustrated by a survey undertaken by the author in 2013. A pre-development survey on Tetney Sands, to the south of Grimsby ahead of construction of a pipeline discovered the recently exposed remains of a shipwreck of probably 19th/20th century date lying in the intertidal zone (Fig. 5).

The wreck lay on intertidal sands around a kilometre from the high water mark but much closer to the low water mark. A site assessment was carried out in June 2013 by the author in order to plan the wreck and to try to carry out augering and small-scale test-pitting through homogenous sand deposits to establish its extent (McCarthy, 2013). At the time of survey the wreck remained almost entirely covered with sand and the only visible elements were a line of ribs (futtocks) defining one edge of the hull, protruding above the sand to a maximum height of 20 cm. The location of the wreck presented a challenge for the recording of the vessel. Although the visit had been planned to coincide with low tide, there was less than an hour available to carry out both test-pitting and survey before the incoming tide covered the vessel again. As the vessel lay on a slightly raised sandbank there was also a risk that spending too much time carrying out survey of the site might result in the tide cutting the surveyors off from the beach. For these reasons it was decided to employ multi-image photogrammetry as the fastest method of making an accurate survey. A series of photos were taken around the wreck in a circular pattern. These were
processed using Agisoft PhotoScan and used to create orthographic plans and elevations. The results of this survey were highly satisfactory and also capture the slight scour pit which had developed around the remains while submerged at high tide. As with the survey at Aberlady, radiance scaling was used to emphasis the details in the renders (Fig. 6). The orthographic plan render was then georeferenced using pre-existing dGPS survey data. The use of multi-image photogrammetry on this occasion meant that an accurate survey of the remains could be carried out in a matter of minutes allowing far more of the brief window of time available to be allocated to other elements of the fieldwork such as interpretation and augering.

6.4. Value of photogrammetry as a practical survey tool for contract-led heritage

These surveys demonstrate how valuable multi-image photogrammetry could be in a contract-led heritage context. In all three cases recording time was very short compared to alternative techniques, overheads were low and the outputs were highly detailed and of sufficient accuracy to meet the objectives of the project. Many multi-image photogrammetry software creators have focused their marketing at sectors other than heritage, for example Agisoft have focused on the mining industry and Autodesk have targeted hobbyists interested in 3D printing. However, the value of a cost-effective, rapid and accurate method for measured survey for cultural heritage is obvious and there are a small but growing number of published archaeological surveys which have used the technique in a contract-led or community engagement. One of the most notable examples operating in the UK is the EU FP7-funded 3DCOFORM Project (Rodriguez-Echavarria et al., 2009) where members of the public have been encouraged to learn how to capture photographic datasets suitable for photogrammetric modelling with the resulting models made available online (http://www.publicsculpturesofsussex.co.uk/). The software used in this case was Arc 3D, one of the earliest examples of an automated photogrammetry pipeline, developed by ESAT-PSI lab of K.U. Leuven in Belgium and the Visual Computing Lab of CNR-ISTI in Italy (Vergauwen and Van Gool, 2006).

Around 80% of archaeological fieldwork in Scotland is developer-led (Historic Scotland, 2012, 13) and at last count over half of the approximately 6000 archaeologists working in the UK were employed in ‘commercial applied archaeology’ (Landward Research, 2011). In order for the heritage sector and the wider community to fully realise the benefits of this new tool for heritage, the technique must be adopted in the commercial as well as academic communities. The practical value of multi-image photogrammetry as a tool for developer-led archaeological survey must be measured against established techniques including as traditional ‘manual survey’ and Terrestrial Laser Scanning (TLS). The crucial considerations are total cost, speed, reliability, accuracy, technical complexity and unique applications of photogrammetry where other techniques would be impossible or unsuitable.

Speed and cost of survey are critical and interconnected issues for all archaeological survey but are particularly important in a contract-led situation. For archaeological units working on a contract basis and competing to undertake contracts, there is a particular emphasis on efficiency. It can be difficult or impossible to devote resources to experimentation with novel and potentially unreliable survey techniques. These units are legally committed to produce specified deliverables to a set standard for their projects. Academic use of the technique is by its nature more experimental and less constrained by pre-defined contractual and budgetary constraints. There are few published examples of multi-image photogrammetry being used in a commercial context in the UK. One of the most notable is the Oxford Archaeology survey of the Viking massacre site at Weymouth (Ducke et al., 2011). As well as the cost of survey the initial cost of purchase of hardware and software for multi-image photogrammetry is an important consideration. There are some very expensive multi-image photogrammetry software packages on the market which are powerful and well-designed but have a limited take-up due to their cost. Tools like 123D Catch are free but cannot produce the kind of results required by most contracts. Other free workflows are available but at present tend to be much more technically demanding.

Fig. 6. An orthographic plan of the wreck generated using photogrammetry.
Fortunately there has been a large investment by the heritage community in Europe and beyond in the creation of free tools for photogrammetric recording and the level of competition between the numerous proprietary software providers suggests costs for those are likely to fall. Projects such as the 3DCOFORM Project (Rodriguez-Echavarria et al., 2009) are helping to establish and promote simple, free and accessible workflows for archaeological use.

As well as cost and speed, the flexibility of photogrammetry is one of its biggest advantages. As long as a camera is available some attempt at a photogrammetric survey can be made. The technique is essentially scale-independent and can be applied to some of the most common types of contracted heritage survey, including historic building recording, small finds recording and topographic survey (using terrestrial or aerial platforms). Because of the minimal preparation required it is also useful for rapid ad hoc recording of the type often required on walkovers and watching briefs. It is particularly well suited for rapid recording of complex, irregular or delicate surfaces which by their nature make traditional recording difficult. For example it can be an excellent way to produce orthographic plans of complex burials or rubble surfaces which are awkward or undesirable to stand on and draw accurately using planimetric means as well as time-consuming to draw because of their lack of flexibility. In many cases the same or better results might be produced using a laser scanner but not without incurring high and often prohibitive costs associated with hardware. The survey at Rubha also illustrates how the technique can be applied to complex subjects with large amounts of self-occlusion. Attempting a laser scan of such sites would normally require a large number of stations to be established. In multi-image photogrammetry each camera location acts like a survey station but requires with far less effort to set up. For heritage organisations who derive their income through contracted work, investment in the technique can therefore result in greater efficiency and enhanced outputs across many types of project.

Although most of the advantages of multi-image photogrammetry in comparison to other techniques must be expressed in relative terms, there are a number of heritage survey applications which might be considered exclusive to photogrammetry. These include the application of the technique to legacy datasets of historical images. There have been a number of successful examples of this using stereo photogrammetry such as the reconstructions of the Bamiyan Buddha statues destroyed by the Taliban in Afghanistan in 2001 (Gruen et al., 2004). In the same way, the original photos of a contemporary multi-image survey retain the potential to be reprocessed in the future for better results. The survey at Rubha also demonstrates another advantage of having a large number of data capture locations. Large numbers of vertical photographs looking through the surface of the water were used to generate 3D data for shallow submerged archaeological features. The use of vertical and near vertical capture locations minimised the effect of refraction and would be impractical to duplicate with a laser scanner. Another unique application is for completely submerged survey, i.e. where the camera and subject are both fully submerged (e.g. Drap, 2012). Although this is more challenging than terrestrial multi-image photogrammetry it is possible to produce excellent 3D data in an environment where laser scanning is not possible.

Accuracy is a major concern for archaeologists working in a developer-led context. Project briefs and industry guidelines usually require that survey be carried out to a set of predefined standards for the accuracy of data capture. One of the most detailed of these is Metric Survey Specifications for Cultural Heritage (Bryan et al., 2009) which largely predates multi-image photogrammetry but which contains applicable standards on point density and accuracy. This guidance suggests that when digitising from a point cloud for illustration at 1:10 scale, the cloud should have a point interval density of not greater than 15 mm. Less dense points clouds are suggested for digitisation at greater scales, up to 750 mm for digitisation for illustration at a 1:500 scale. English Heritage guidelines state that recorded points must be with the following accuracy ranges for standard scale output:

- for 1:50 output scale, 9 mm in reality
- for 1:20 output scale, 4 mm in reality
- for 1:10 output scale, 2 mm in reality

Whether these levels of accuracy can be achieved is largely dependent on the workflow adopted. The accuracy of a multi-image photogrammetric survey can be affected by many variables including the quality of the photos, the complexity of the lens distortion, the depth of field, the texture of the surfaces and the layout of the ‘stations’. There have been a number of studies which have demonstrated that multi-image photogrammetry can achieve results approaching or even superior to those from laser scanners under the right conditions (Pierrot-Deseilligny et al., 2011; Georgantas et al., 2012; Chandler and Fryer, 2013). As mentioned above, the same equipment might be used to capture both a landscape and a pot sherd. In this case the accuracy of the landscape is likely to be much lower in real terms than the pot sherd. At the micro scale, Adamtech, makers of the multi-image photogrammetry software 3DM Analyst cite an example of a dental survey which achieved accuracy of approximately 15 microns ‘using inexpensive off-the-shelf digital cameras and lenses’ (http://www.adamtech.com.au/Blog/?p=68 Accessed 16/01/2013). During the recent laser scan of Stonehenge, multi-image photogrammetric models of carved faces of individual stones were made as the 0.5 mm density laser scan was insufficiently detailed to capture some of the fainter carvings (Abbott and Anderson-Whymark, 2012). Ultimately the important question contact-led heritage bodies must consider is not how accurate the technique is in general but how accurate it can be. For now it is enough to state that, if set up properly, multi-image photogrammetry is capable of results well within English Heritage guidelines and can be a meaningful alternative to laser-scanning. Deciding whether multi-image photogrammetry is an appropriate approach with a low risk of failure in any given case is ultimately a judgement call and requires experience and investment.

The most valuable application of multi-image photogrammetry may yet prove to be in facilitating community involvement in archaeological recording as well as allowing for the easy creation of interactive 3D models and fly-throughs which allow the public to engage with their heritage sites in much more immersive way than that afforded by plans and sections. Important examples of projects which demonstrate this well include the aforementioned co-funded FP7-funded 3DCOFORM Project (Rodriguez-Echavarria et al., 2009) and the Northumberland and Durham Rock Art Project (Bryan and Chandler, 2008). Both of these projects centred on encouraging members of the public to record heritage sites using photogrammetry. The survey by the members of the Young Archaeologists’ Club at Aberlady demonstrates how straightforward this can be and it is likely that there will be many more large-scale projects of this type in the future.

The photogrammetric surveys undertaken by the author with WA Heritage and the Young Archaeologists’ Club were presented in poster form at an Institute for Archaeologists (IFA) Workshop held in Edinburgh in December 2012. The IFA is a professional organisation which sets standards and issues guidelines and which draws a significant proportion of its membership from the contract-led heritage sector. The seminar focused on how surveys are carried
out and presented and drew together some of Scotland’s leading survey practitioners. The response of the professional archaeo-
logical surveyors present was cautiously positive and the attendees had an impromptu group discussion on the merits and challenges of the technique. One of the most significant issues raised in the group discussion was the risk that the increasing use of photo-
grammetry, TLS and other remote sensing techniques could start to replace more traditional manual survey methods. It was felt that this could lead to high resolution surveys of heritage features without an appropriate level of on-site interpretation of phasing and context. This is certainly a real risk and one that heritage managers will need to keep in mind when undertaking or commissioning photogrammetry/TLS surveys. However while it is true that photogrammetry and other remote-sensing techniques should not replace professional interpretation during surveys, digital recording can be an aid to analysis rather than a replace-
ment. For example the detailed 3-Dimensional models produced at Rubha were found to be key in interpreting the phasing of the site, highlighting the variations in the size of stones used in different parts of the site. When compared to traditional surveys, 3-
Dimensional recording produces a more objective record of the surface of a feature, making it easier for those who have not seen the site in person to make their own judgements, and if necessary, re-interprets.

7. Conclusion

De Reu et al. (2013) recently stated that multi-image photo-
grammetry offers ‘better documentation of in-situ structures for future research and a higher public participation and awareness for the archaeological heritage’. It is clear that within a few years the technique will make the leap from its current application in aca-
demic contexts or as an ‘add-on’ for contract-led archaeology to a standard part of the archaeologist’s toolbox across the entire her-
itage sector.

This will undoubtedly happen naturally over time but there are a number of things which can be done to facilitate the process.

Idea-sharing platforms such as conferences and workshops which include both academics and the developer-led sector will promote skill-sharing and understanding of data management, archiving and interpretation. In some cases there may also be a need to re-
view current survey guidance which predates the release of current multi-image photogrammetry software (e.g. Bryan et al., 2009; Barnes, 2011). There is a particular need for technical guidance on recommended pipelines/workflows, from data capture through to archiving, based if possible, on free software. This will greatly reduce the burden in terms of research and expense in the commer-
cial sector and will ultimately lead to an enhanced record and understanding of our archaeological heritage.

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