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Abstract A recent digital public archaeology project (HeritageTogether) sought to build a series of 3D ditigal models using photogrammetry from crowd-sourced images. The project saw over 13000 digital images being donated, and resulted in models of some 78 sites, providing resources for researchers, and condition surveys. The project demonstrated that digital public archaeology does not stop at the 'trowel's edge', and that collaborative post-excavation analysis and generation of research processes are as important as time in the field. We emphasise in this contribution that our methodologies, as much as our research outputs, can be fruitfully co-produced in public archaeology projects.

Small Works, Big Stories. Methodological approaches to photogrammetry through crowd-sourcing experiences

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Abstract—**A recent digital public archaeology project (HeritageTogether) sought to build a series of 3D ditigal models using photogrammetry from crowd-sourced images. The project saw over 13000 digital images being donated, and resulted in models of some 78 sites, providing resources for researchers, and condition surveys. The project demonstrated that digital public archaeology does not stop at the 'trowel's edge', and that collaborative post-excavation analysis and generation of research processes are as important as time in the field. We emphasise in this contribution that our methodologies, as much as our research outputs, can be fruitfully co-produced in public archaeology projects.**

I. INTRODUCTION

HeritageTogether is the umbrella name for a research collaboration between Bangor, Manchester Metropolitan and Aberystwyth universities, Gwynedd Archaeological Trust, and a collective of volunteer digital archaeologists working on recording the prehistoric archaeological heritage of north Wales (and beyond). The project uses digital photographic techniques as well as recent developments in digital 3D modelling, and relies on 'citizen scientists' to contribute data (photographs) as the basis for its analysis. The research outputs of the project include contemporary condition surveys of sites, which will prove invaluable in terms of protecting the historic environment of this part of Wales. Other new archaeological research outputs include information on the alignments of sites, the nature of the raw materials utilised for site construction, and the dressing and rock art decoration of standing stones, as well as other aspects of the landscape archaeology of the sites surveyed.

The project has also included a degree of mutual education between all members of the project, in terms of widespread application of digital photogrammetric recording techniques to prehistoric archaeological sites. Here we present the results of our experience as HeritageTogether in terms of doing digital photogrammetry as a form of digital public archaeology (DPA). These co-produced methodological findings were recorded by members of the team as the project progressed, and benefited both from discussion on site while doing fieldwork and with contributors afterwards. We believe that these methodological findings, which were the result of a team effort during the project, are as much part of the citizen science crowd-sourced project findings as the time spent in the field, and the new data produced. This may be especially true when working with a diverse group of digital archaeologists, on a range of sites in the field, and using Internet fora and emails. The scale of our dataset (in November 2014, 13,064 digital images had been co-produced; Griffiths et al. this issue [6]) over some 78 sites has led to the HeritageTogether team co-producing our methodologies through practice.

We believe that digital public archaeology does not stop at the 'trowel's edge', and collaborative post-excavation analysis and research processes are as important as time in the field. What we want to emphasise

in this contribution is that our methodologies, as much as our research outputs, can be fruitfully co-produced in public archaeology projects. We suggest that projects that emphasise only the field results of citizen scientists – whether the results of their excavation in more traditional archaeological projects or, in this case, the photographic data – are recognising only part of these citizen scientists' contributions.

II. METHODOLOGY

The application of digital photogrammetry develops a long history of georectification in archaeological imagery, as both a means to record sites, monuments and portable material culture, and as a means to research spatial aspects of archaeological data. Digital photogrammetry uses structure-from-motion as a means to produce 3D models of archaeological objects. Applications of archaeological photogrammetry have developed significantly in recent years, as access to greater processing power, personal computing, and digital photographic solutions have become more commonplace. With the advent of high-quality digital photography, photogrammetry has come to be used alongside laser-scanning to provide reliable texture mapping for the untextured models produced by the scanning equipment (e.g. Al-Kheder et al. 2009 [1]; Ergun et al. 2010 [5]; Lerma et al. 2010 [9]). Photogrammetry is now being used professionally to record and research a variety of archaeological subjects, from Galician petroglyphs (Sans et al. 2010 [13]) to the Dome of the Rock (Al-Ruzouq et al. 2012 [2]) and the cathedral of Santiago de Compostela (Martinez et al. 2013 [10]).

As far back as 2004, it was recognised that the speed and low-cost nature of digital photogrammetry meant that it had the potential to become the technology of choice for 3D modelling in all but the most high precision of applications (Boehler and Marbs 2004 [3], 298). The latest developments in processing software, for example Autodesk's 123D Catch (first published in 2009) and Agisoft Photoscan (first published in 2013) allow the automatic recognition and combination of images without the necessity for reference points or known dimensions from the subject being modelled.

Our project uses Agisoft Photoscan, a commercially available computer programme, to identify common points in multiple digital images. The metadata contained in the unadulterated file allows the program to adjust for barrel distortion and depth of field, rendering the camera calibration required for previous photogrammetric approaches unnecessary. By changing the camera position between different images, it is possible to generate many common points, with differences between the location of common points allowing the program to generate volumes for photographic subjects. In addition, photographic subjects can be associated with known geographic coordinates, which facilitates accurate scaling and geolocation. This in turn allows landscape approaches to the analysis of the models by positioning them in 3D space in relation to other models or features, in order to investigate the setting of sites or monuments with reference to their orientation, or the wider geographical context of sites. Rendering an accurate volumetric model of a site or monument means that it is possible to produce metric measurements that may not have been recorded or analysed before.

In a study comparing this automatic method with earlier software reliant on reference metrics and stereo-pair images, it was found that automatic algorithms delivered highly comparable levels of detail and accuracy, without requiring advanced knowledge of surveying or 3D modelling software (Krasic and Pejic 2014 [8], 282). Automatic digital photogrammetry therefore opens the way for a democratic and low-cost approach to generating archaeological data. The accessibility of these approaches provides the means for members of the public to produce really high-quality research data as part of a digital citizen science project, which can make 'real' contributions to archaeological understandings.

HeritageTogether differs from many digital public archaeology projects in our use of large-scale digital data generated by members of the public (see Griffiths et al. this issue [6]). Our data sample has given us scope to explore the methodologies of co-producing 3D photogrammetric models, and of the challenges and affordances of producing data in different ways. Critically, by working with a range of users on diverse sites, by designing guidelines for the project, and by responding to queries at workshops, lectures, and on the online forum, our methodologies have been developed by citizen scientists. As the project developed, we realised that as well as the more standard research outputs (the site models that provide condition surveys, and site-specific research data), the development of the method with members of the public was an important project output in itself (Moshenska 2014 [11]). The conversations that we had, and the ways we learnt through practice with members of the public, were processes that were due to the citizen science emphasis of the project. Increasingly as the project developed, our practice (meaning everyone involved with HeritageTogether research) was

co-produced.

1) Case study 1: the Llanfechell Triangle
2) Case study 2: Bryn Celli Ddu passage tomb
3) Case study 3: Achnacreebeag

Three case studies are presented here to illustrate a range of learning outcomes and methodological issues that were developed in consultation with members of the public who worked on sites for the HeritageTogether research. We detail them as a series of practical approaches for doing digital photogrammetry. As our project developed, so did our methodology. This article represents the co-produced outcomes of this approach to doing digital public archaeology in practice.

A. Case study 1: the Llanfechell Triangle

The Llanfechell Triangle (SH3639791688) is an irregular arrangement of standing stones near the village of Llanfechell, Anglesey, north Wales. The stones are roughly 2m in height, with the long axes in plan all aligned roughly north-west to south-east (Figure 1). The stones were probably erected in the late Neolithic or Early Bronze Age. Recording the monument for the HeritageTogether project emphasised several methodological issues.

When recording objects in three dimensions, it is important to try and capture all planes of an individual object. For a site with several component features, for example a group of standing stones such as the Llanfechell Triangle, it is necessary to record all planes of each individual stone; all the sides, any under-hangs or over-hangs, any details in the texture of the surface, as well as the planes on the top of a monument. For relatively tall structures or monuments (i.e. taller than the photographer), it is necessary to find some means to record from above. A lack of photographs from above may lead to a scatter of erroneous points in the model, emanating from the top of any vertical faces. Similarly, it is necessary to photograph small objects from above in order to 'flatten' any upright face. This is particularly important, for example, when recording small standing stones.

In sites composed of multiple elements, it is necessary to relate the constituent features to each other. 'Positioning' or 'contextual' images allow the program to identify how each element is spatially related. In order to tie together related monuments within an archaeological landscape, we have found that a combination of wide-angle contextual photographs that take in more than one monument and a series of linking photographs, where the photographer shoots a sequence of images moving

Fig. 1: Photogrammetrically derived model of the Llanfechell Triangle

between two monuments, can advantageously be used together. For monuments that include several elements, it is advisable to vary between portrait and landscape photographs in order to maximise both monument and background coverage. Figure 2 demonstrates the positioning of detail and contextual images taken at the Llanfechell Triangle.
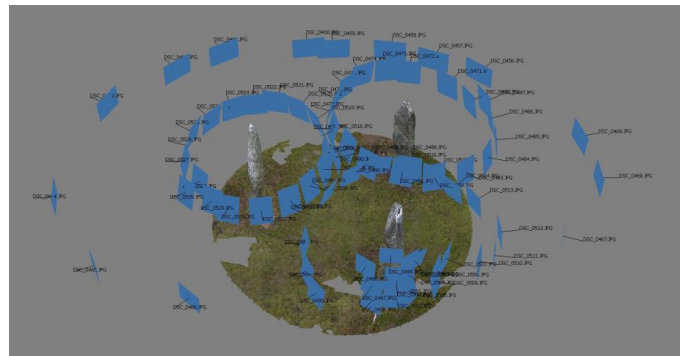

Fig. 2: The positioning of detail and contextual images at the Llanfechell Triangle

In many cases it may be necessary to strike a pragmatic, time-effective, balance between levels of detail of parts of a monument and the spatial coverage required. A feasible workaround for this can be to use fewer wider area photographs for simple structural or general topographic recording, with more detailed close-up shots used in complex areas of monuments, or those with specific features that require higher precision modelling. HeritageTogether found this a useful approach, for example, when recording rock art panels in archaeological monuments or landscapes.

1) Conclusions:

- It is necessary to record all planes of each individual stone; all the sides, any under-hangs or over-hangs, any details in the texture of the surface, as well as the planes on the top of a monument.
- In sites with multiple elements, 'positioning' or 'contextual' images allow images to be related to each other.
- A combination of wide-angle contextual photographs that take in more than one element of the monument, and a series of linking photographs moving between elements of the monument, can be used in conjunction.
- In cases where a monument has more than one element, using a combination of portrait and landscape photographs maximises both monument and background coverage.
- The detail of a survey can vary, with less dense photographic coverage for relatively simple areas, and more detail in complex parts of a monument.
- To avoid vertical distortion on tall monuments, take photographs from the 'corners' of objects at oblique angles to the structure.

B. Case study 2: Bryn Celli Ddu passage tomb

The Llanfechell Triangle and Bryn Celli Ddu passage tomb (SH5076170185) represent very different types of monument in terms of the constraints they place on digital photogrammetric recording. In its contemporary form, Bryn Celli Ddu comprises a partially denuded circular mound (Figure 3), with a semi-enclosed chamber and passage. Bryn Celli Ddu is a later Neolithic passage grave in the Atlantic tradition (Burrow 2010 [4]). While the passage and chamber are stone built, and the mound partially defined by stone kerbs, the most imposing aspect of the monument is the grass-covered mound. Modelling this monument required the team to address issues of photographing the interior of confined spaces, but also accurately producing a model of an undifferentiated grass surface. Recording the monument benefited from the crowd-sourcing approach, because the monument is so well known numerous people using different cameras (including camera phone images), shooting from different positions and providing varying degrees of coverage, contributed data to the models; these included digital photogrammetry of the site from kite platforms. Some of these images were relatively blurred, but were viable in the modelling because of the elevation from which images were taken.

Photographing the interior of the monument includes the obvious challenges of marrying exposure with low

Fig. 3: Photogrammetrically derived model of Bryn Celli Ddu showing undifferentiated grass mound

light levels and appropriate detail. HeritageTogether found that, in confined spaces, combining photographs taken at oblique angles to the target surface with photographs that are produced perpendicular to the plane of the target surface (i.e. looking straight at the flat surface) to be a useful approach. The combination of oblique photographs and transects of perpendicular images is also especially valuable when recording any monument or structure with very tall features. In these cases it is advisable to photograph objects along a transect running parallel to the object, but adding photographs taken at oblique angles at the edges of any vertical faces. These approaches counteract the effect of barrel distortion in the lens along the vertical axis, and ensure that resultant models are undistorted (Figure 4).
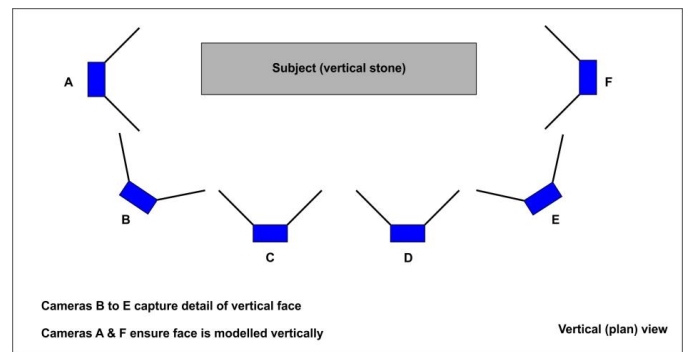

Fig. 4: Photo positions for modelling vertical subjects

A particular challenge in photographing archaeological earthworks for photogrammetric modelling is differentiating between large areas of sites or monuments that possess a very similar texture, with few unique features. In the case of the mound at Bryn Celli Ddu for example, but also for other grass-covered earthworks,

photogrammetric software may not be able to identify unique targets. These can be supplied to members of the public working with a team. If unique targets are to be used these can be georeferenced in landscape models. As with any form of survey, thought needs to be given to the duration for which spatial control is required, so that allowance can be made for future use.

Alternatively, unique points in the landscape such as gateways, field boundaries, and so on, which appear in the background of the picture, can be used to locate earthworks. For topographic landscape work, photographs are required perpendicular to the plan of the landscape being recorded (Griffiths et al. in prep. [7]). This is not usually achievable using terrestrial recording methods, and an aerial platform is required. In most instances, this limits the public accessibility of digital photogrammetry work, as individuals may not have access to aerial platforms. This said, significant work making aerial survey accessible to groups wanting to do their own digital survey work has been undertaken by John Wells and the Scottish National Aerial Photography Scheme (SNAPS).

1) Conclusions:

- When working in confined spaces, it is useful to combine photographs taken at oblique angles to the target surface with photographs that are produced perpendicular to the plane of the target surface.
- When working on large undifferentiated surfaces such as fields, unique points or targets can be employed. If these are not available, landscape features beyond the photographic subject – such as fences, gateways, power-lines, field boundaries – can be used to locate earthworks.
- If it is possible, and safe, use height to get further away from the subject. This will help with earthworks.

C. Case study 3: Achnacreebeag

Achnacreebeag (NM92963639) is a Neolithic chambered cairn in Argyll and Bute, Scotland, consisting of two burial chambers, which were covered by a stone mound (Ritchie 1973 [12]). Achnacreebeag has been particularly important in terms of national debates concerning the first Neolithic societies in Britain and Ireland (e.g. Sheridan 2012 [14]; Whittle et al. 2011 [15]). However, interpretation and visualisation of the site in the contemporary literature relies heavily on plans generated as part of the mid-20th century excavation (Ritchie 1973 [12], 32). The dimensions and location of the site are directly relevant to its importance. Never

before has a 3D colour representation of the monument been available to aid in its interpretation.

Achnacreebeag was recorded by members of the team as part of our wider work on comparable sites for the north Wales monuments, which includes contributions from members of the public from Orkney, Jersey, and salaried members of the team in Ireland and Scotland. It presented a number of site-specific recording issues such as the presence of water on the site (which produces 'bounce') and rainy conditions (which present the usual photographic constraints). The creation of the model of the site has wider implications for public archaeological research and dissemination. The potential impact of digital photogrammetry on archaeological research should be noted here. Relatively limited or small surveys can result in important archaeological models; individual contributions from citizen scientists have the potential to have disproportionately large impacts on our understanding of the archaeological record.

For the model presented here (Figure 5), relatively few images were employed; 195 photographs were used in this instance. Additional photographs were taken by a member of the team on a Neolithic Studies Group trip with a scale to generate metric data. Higher resolution models are not directly dictated by the number of photographs (though a minimum number are required to guarantee coverage and a fully 3D model), but by the resolution of the images used to generate the model. In order to afford maximum resolution, the distance from the subject being photographed and the use of a high-resolution digital camera (higher than 12 megapixels) are key. Accounting for these criteria, digital public archaeologists can produce timely, significant and important research using relatively limited resources.

Fig. 5: Photogrammetrically derived model of the chambers at Achnacreebeag

1) Conclusions:

- Photogrammetry can be a relatively quick and forgiving recording technique.

- For remote and important sites, individual citizen scientists can have a disproportional impact on national research and debates.

III. CONCLUSIONS

Digital photogrammetric survey in many ways represents an ideal form of public archaeology. The technology behind the technique is relatively simple and forgiving; images are better in focus but otherwise there are few stipulations. We were surprised by the ability to process even very blurred images generated on some of our community aerial kite-flying surveys into digital land-surface models. Surveys of a site, even of a relatively complex monument, can be achieved comparatively quickly. Surveys can be undertaken using any form of digital camera, including ubiquitous camera phones if their image quality is of a sufficiently high resolution. Digitally recording monuments could allow members of the public, who for a variety of reasons might not be willing or able to engage with other forms of fieldwork, to become part of archaeology, and to generate important archaeological research data themselves.

As well as the unparalleled record of sites in our study area, the HeritageTogether project has allowed the co-production of our method in practice. Our methodological outcomes (see Appendix) are highly relevant to archaeological projects that may wish to engage members of the public by employing digital photogrammetry. As well as crowd-sourcing our research data through collaboration, we have co-produced a method as a result of digital photogrammetric recording at over 80 archaeological sites, using nearly 200,000 images, and worked with members of the public on and off site in a range of settings. We feel strongly that these practical, methodological digital public research outcomes are as much part of the success of the project as its other outputs. We value the methodological outputs of the project detailed here; they represent our co-produced reflections on the practice of archaeology. We believe that public archaeology does not begin and end at the trowel's edge, and should include developed engagement in all aspects of project planning, fieldwork, and post-excavation processes for citizen scientists who wish it. If we do not engage and support members of the public with project planning and reporting, we are doing interested people a disservice in only affording a very partial view of what archaeology is. We believe part of this should include valuing and reporting the work undertaken in partnership with members of the public in the development of methodological approaches.

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The English language HeritageTogether crowd-sourced photogrammetric methodology (the Welsh language version is available on the project website: http://heritagetogether.org/)

Simple monuments

Try and capture all planes of each object (all the sides, any under-hangs or over-hangs, any details in the texture of the surface, as well as the planes on the top of a monument)

For relatively tall structures or monuments (i.e. taller than the photographer), it is necessary to find some means to record from above.

Used oblique photographs and transects of perpendicular images with very tall features.

To avoid vertical distortion on tall objects take photography from the 'corners' of objects that record the vertical planes at oblique angles.

Complex multi-element monuments

In sites with multiple elements, 'positioning' or 'contextual' images allow the program to relate elements each to the other.

A combination of wide-angle contextual photographs that take in more than one monument, and a series of linking photographs where the photographer shoots a sequence of images moving between two monuments can usefully be used in conjunction.

In the cases of monuments which include several elements, it is advisable to vary between portrait and landscape photographs in order to maximise both monument and background coverage.

Consider varying the detail of survey: use fewer wider area photographs for simple structural or general topographic recording, with more detailed close-up shots used in complex areas

Confined spaces

Combining photographs taken at oblique angles to the target surface, with photographs which are produced perpendicular to the plane of the target surface (i.e. looking straight at the flat surface).

Earth works and grassed areas

Consider using unique targets.

Include unique points in the landscape such as gateways, field boundaries, to locate earthworks.

Use height (safely) if possible!

Research value

Even a single survey can produce valuable archaeological data on important or unrecorded sites. Even a relatively few photos can make a significant di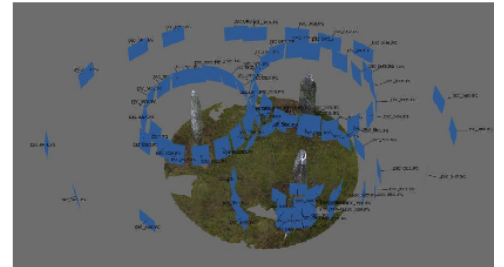fference to archaeological understandings.