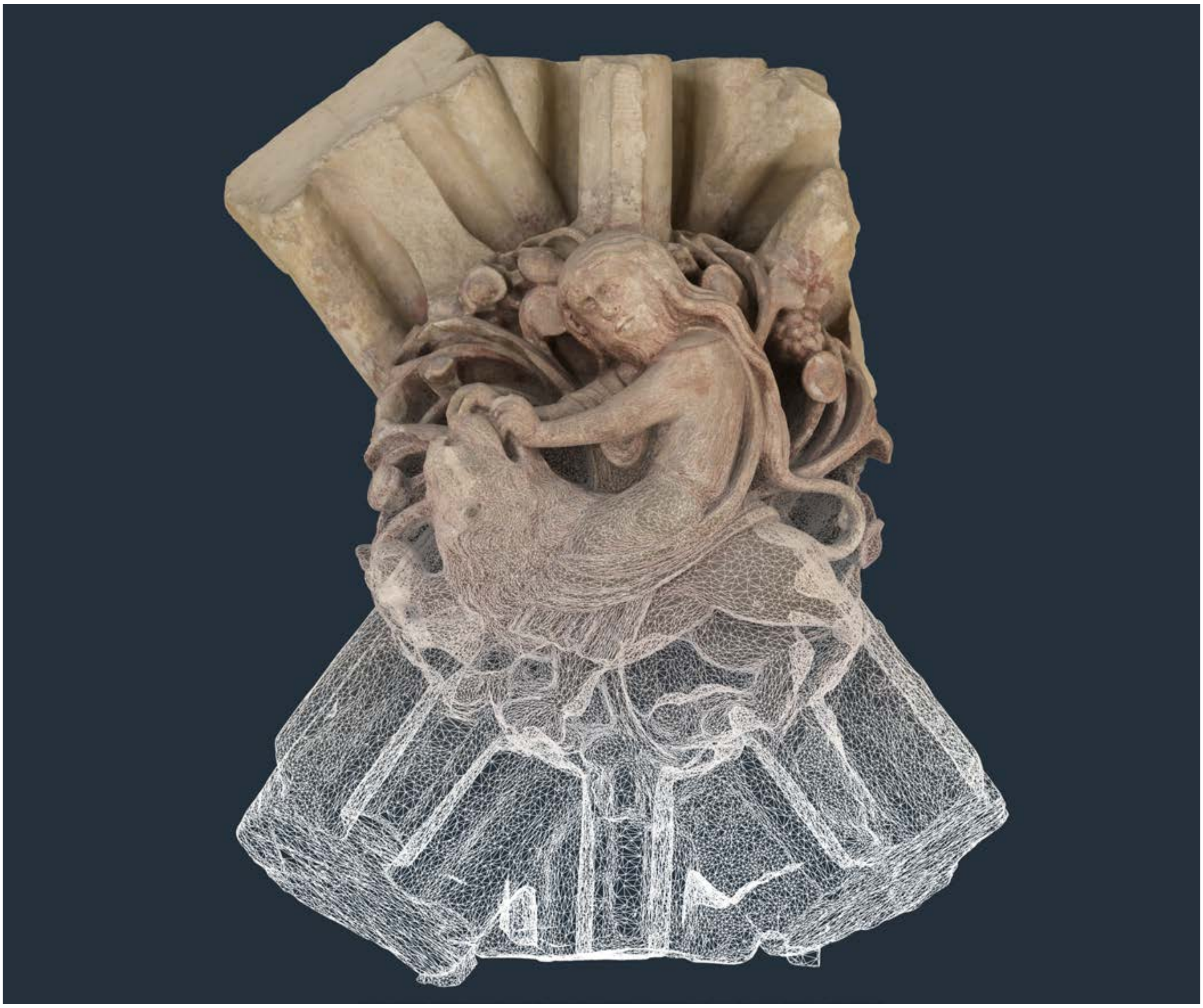
Historic England

Photogrammetric Applications for Cultural Heritage

Guidance for Good Practice



Summary

This guidance covers the practical application of photogrammetry in recording cultural heritage, with particular reference to structure from motion (SfM) techniques. Our audience for this document includes survey contractors, archaeological contractors, voluntary organisations and specialists. Photogrammetric image acquisition and processing, until recently requiring a considerable investment in hardware and software, are now possible at a fraction of their former cost. This has led to a huge increase in the use of photogrammetry in cultural heritage recording. The skills required to apply the techniques successfully and accurately are discussed, and background information on how various parts of the process work is provided so that better results can be achieved through better understanding.

Photogrammetry is characterised by its versatility, and is applicable over a wide range of scales, from landscapes to small objects. The particular requirements needed at these different scales are outlined, and both imaging techniques and useful ancillary equipment are described. The different types of outputs are discussed, including their suitability for further interrogation using a range of established analytical techniques and the presentation options available. A range of case studies illustrates the application of photogrammetry across a variety of projects that broadly reflect the areas discussed in the text. This document is one of a number of Historic England technical advice documents on how to survey historic places.

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Front cover
13th century roof boss depicting Samson wrestling a lion, Hailes Abbey, Gloucestershire.

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Introduction

This guidance covers the application of photogrammetry in cultural heritage with particular reference to structure from motion (SfM) techniques. The aim is to raise awareness of the issues that are commonly encountered, rather than to deal with all aspects of photogrammetric processing in depth. There are many potential uses for this technique across a wide variety of scales, ranging from landscapes (for example 10km^2 or more) to small objects (for example 10mm^3). The different outputs are suitable for a range of established analytical techniques and offer many presentation options.

Photogrammetric image acquisition and processing, until recently requiring a considerable investment in hardware, software, expertise and time, is now possible at a fraction of its former cost. The advent of more affordable photogrammetric software over the last few years, in particular the use of SfM techniques, has seen an explosion in its use in archaeology. This has been helped by the development of relatively cheap digital cameras capable of capturing high-quality imagery, and by advances in the processing capability of personal computers. Additionally, the development of small unmanned aircraft (SUA), which can be used to capture low-level aerial imagery, has contributed by providing an easy method for recording individual sites.

Core skills

In order to use photogrammetric techniques successfully in archaeology, a number of core skills are required.

Photography

You need an understanding of how to use cameras and related equipment to achieve the best possible images in different circumstances.

Photogrammetry

You need an understanding of the image arrangements needed to achieve the best coverage of the target and ensure the highest accuracy of the models produced. You will need some knowledge of the camera distortions that can affect the quality of the results.

Survey

You need an understanding of the appropriate level of detail, scale, orientation and control for different projects. You need to know when it is appropriate to use photogrammetry and when another surveying method would be more suitable to achieve the desired product.

You need to be able to organise the stages of a project in an efficient way. You also need an understanding of the importance of metric accuracy, and of the methods available to quantify and improve it.

Software

You not only need to know about photogrammetric software packages, but also those required for image processing and later digitisation and analysis, such as computer-aided design (CAD) software and geographic information systems (GIS).

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Archaeology/architecture

You need to be able to interpret and use the data generated to answer the questions being asked.

Data presentation

You need to be able to present the data in a clear, unambiguous and aesthetically pleasing format, using established conventions.

These skills can be shared across a team, but it is important that all are present.

Appropriate use of different survey techniques

Broadly speaking, survey techniques can be divided into mass capture and selective methods. Mass capture methods, such as three-dimensional (3D) laser scanning and photogrammetry, are characterised by large amounts of undifferentiated data at the point of capture and selection from that data off-site. Selective methods, such as global navigation satellite systems (GNSS), use of total station theodolites (TSTs) and hand-drawn survey, are usually characterised by the selection of data measured at the point of capture (Figure 1).

One survey technique on its own rarely provides the perfect solution for most recording and analysis projects, and often requires augmenting with data derived from different sources or methods. Your focus should be on the suitability of the products for the task at hand and the required deliverables rather than the method used to derive them. Similarly, although the accuracy of photogrammetric reconstruction is affected by a number of factors, it is wise to remain focused on the desired performance and use of the product rather than obtaining the highest possible accuracy and density of reconstruction under all circumstances. Photogrammetrically processed imagery can produce resolutions far in excess of the required result, which often leads to time being spent on processing unnecessary data, the handling of very large files and subsequently the need to decimate the derived data in order to achieve a usable and suitable product. For example, specifying a 10mm ground sample

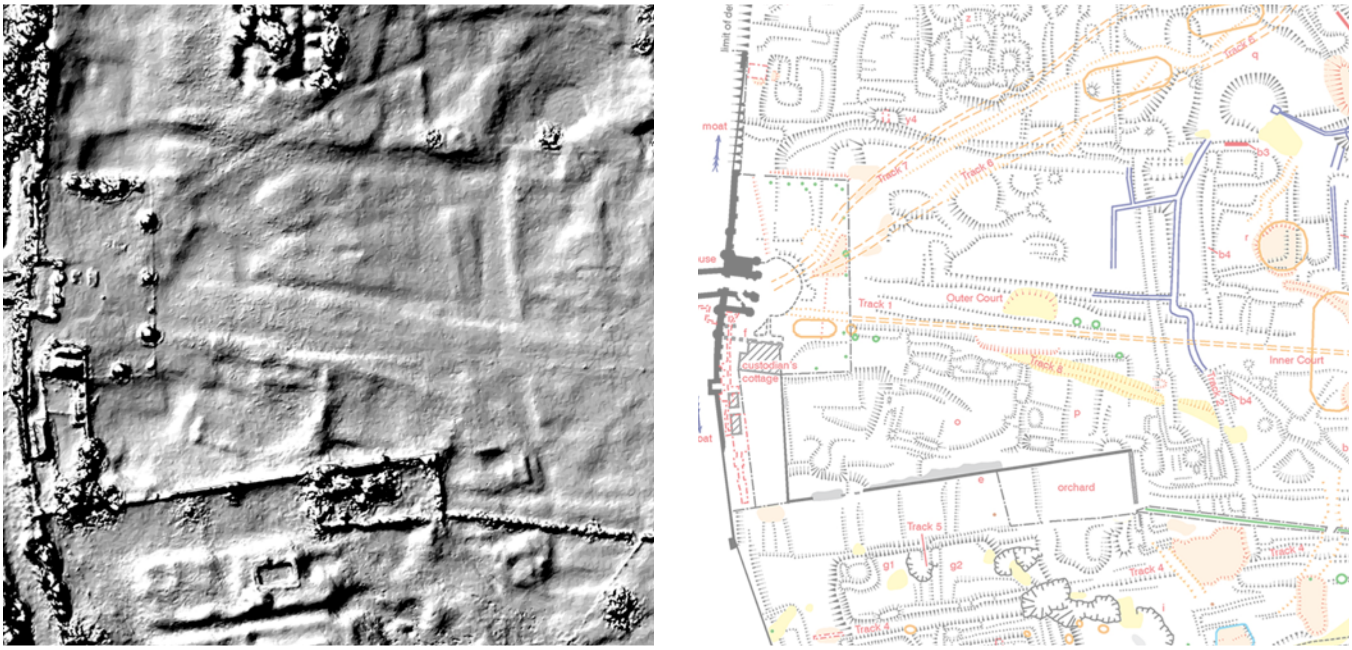


Figure 1
Hillshaded DEM derived from mass capture techniques (left); highly selective interpretative linework derived by GNSS survey of the same area (right).

distance (GSD; the distance on the ground between adjacent pixel centres in the image) for vertical aerial photography when the analytical output is intended to perform at a scale of 1:1,000 is pointless. Specifying such a GSD over a rough grassed area would also be unhelpful, leading to more data to be handled with no visible benefit to the product whatever the desired scale of output, and the creation of unnecessarily large archives. This holds true for all circumstances in which photogrammetry is used: the achievable densities of point cloud and mesh can easily exceed the requirements of the product and the capabilities of the hardware employed. Although results obtained using digital single lens reflex cameras (DSLRs) are almost always better than those from point-and-shoot cameras, the problems encountered when deploying them (especially in the case of fixed-wing SUA or kites) can outweigh the benefits, and in some circumstances it can be better to use a good compact or mirrorless camera. Careful thought should therefore be given to the requirements of the end product before the acquisition and processing of images is even started. However, it is always better to start with a slightly higher quality product in mind, which can be reduced to the required output density later, rather than a lower resolution product: if the data is not there to start with, it cannot be reliably interpolated.

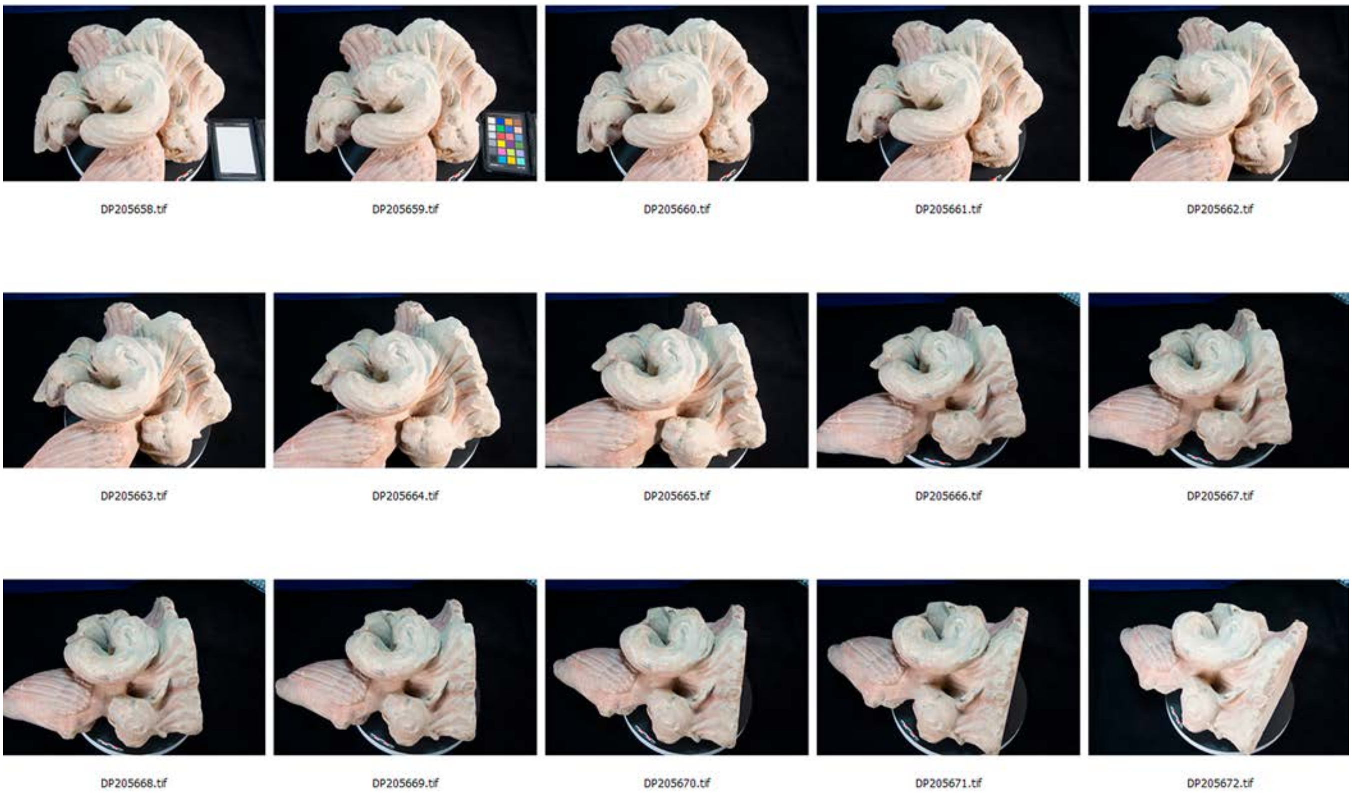


Figure 2:
Overlapping images of a subject.

1 Basic Principles

This section provides an elementary introduction to some of the general principles underpinning the photogrammetric process, and shows, in a highly condensed way, how it works and why. Many of the operational principles derived from more traditional stereo photogrammetry are equally applicable to more recent, highly automated multi-image convergent photogrammetric developments that use a combination of SfM and multi-view stereo (MVS) workflows. In practice, much of this will be hidden from the user, but a better understanding of the basic processes involved will lead to improved configuration of input imagery, more efficient processing and more accurate results.

1.1 Basic procedure

The basic procedure for surveying most subjects, whatever the scale, is as follows.

Image capture

A series of overlapping images of the subject is taken (Figure 2). The example in Figure 2 is a piece of carved stonework.

Image matching

Tie points on the images are matched (Figure 3) and the camera orientations deduced (Figure 4).

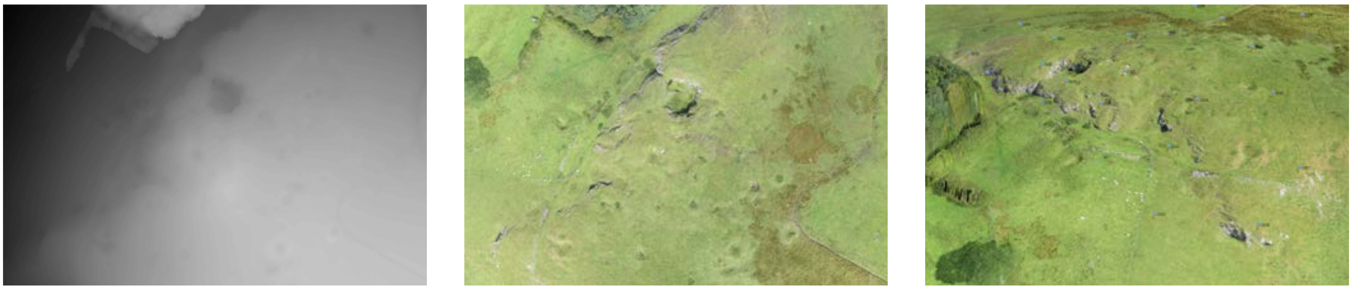
Dense point cloud generation

A dense point cloud is generated, comprising all the possible matches (or a subset of all the possible matches, depending on settings) between the images projected in 3D space (Figure 5).

Figure 3
Tie points detected on the images.

Figure 4 (top)
Interior and exterior orientations of cameras calculated.

Figure 5 (bottom)
The dense point cloud, comprising all possible matches.



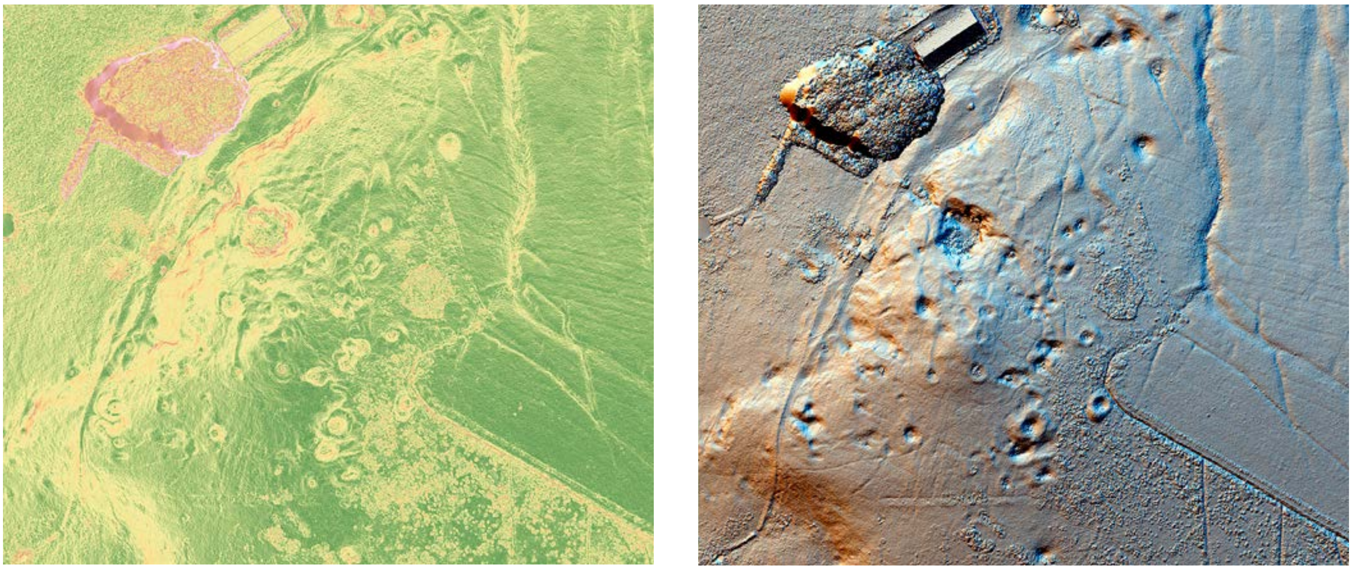


Figure 6 (top)
A range of possible outputs. From left to right: DEM, ortho-image and textured model.

Figure 7 (bottom)
Analytical products derived from the outputs shown in Figure 6. Left: Slope analysis, Right: Multi-directional hillshade.

Secondary product generation

A range of possibilities exists for the outputs, including ortho-images, digital elevation models (DEMs) and textured meshes. Figure 6 shows examples from aerial imagery. Not all products are suitable for all subjects.

Analysis and/or presentation of results

Further analysis of the products can be carried using other software (Figure 7), or the models can be exported directly for visualisation purposes.

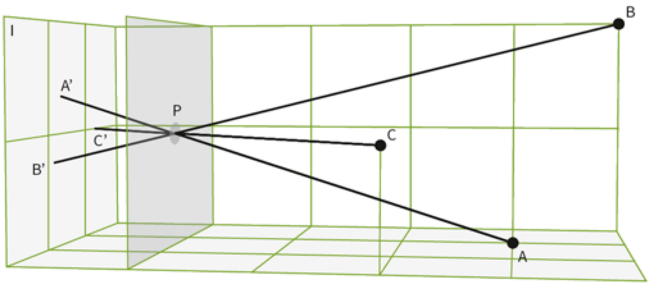
The principles underlying each of these stages are outlined in more detail in section 1.2 on The chief ray and the principles of intersection and section 1.6 Measurement from single, paired or multiple images.

1.2 The chief ray and the principles of intersection

When an image is captured by a normal camera, any point on that image represents the convergence of many light rays. For photogrammetric purposes, the ray of interest is that which theoretically passes in a straight line from the object point (A, B, C), through the perspective (or projection) centre at the back of the lens assembly (P), and onto the image plane (I) at positions A', B' and C' (Figure 8). This ray is often referred to as the chief ray (Fryer *et al* 2007). If the interior and exterior orientations (see section 1.4 Interior and exterior orientation) of multiple cameras are known, then the intersection of the chief rays representing the same object point in the images will define the position of the object point in space (Figure 9). This process can be applied across all, or a sample of, pixels for which there are correspondents in other images. It is important to note, therefore, that any part of the subject that is not shown in at least two images cannot be reconstructed.

1.3 Collinearity

Given the assumption that the object point, camera perspective centre and image point are in a straight line, in order to translate between the two-dimensional (2D) image coordinate system and the 3D ‘real-world’ coordinate system of the subject, transformations must be applied. These transformations are known as the collinearity equations, and are based on an ideal camera as shown in Figure 8, in other words one in which there are no distortions and planarity (flatness) of the sensor is assumed. In such a camera, there would be no geometric distortion from the lens imaging system, and the transformation from 3D object space to 2D image space is done using a perfect, central projection system. In normal use, however, there are several factors that complicate the situation and must be accounted for. In real cameras there are always geometric distortions, which means that the image points are slightly out of position according to the idealised central projection. These deviations from the ideal must be quantified, described mathematically and compensated for. As well as lens distortion, other factors that can affect the outcome include refraction and non-planar image sensors. Refraction is not normally an issue in most archaeological contexts, but comes into play when oblique aerial images are shot at relatively high altitude. In most digital cameras planarity of the sensor can be safely assumed.



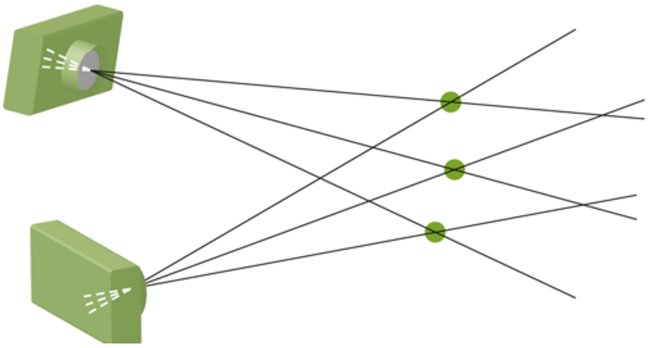


Figure 8 (top)
Principle of the chief ray for any object point.

Figure 9 (bottom)
Intersection of rays from two images defining object points in 3D space.

1.4 Interior and exterior orientation

The model describing the geometric properties of the camera and lens system is known as the inner or interior orientation, sometimes also referred to as camera intrinsics (Luhmann *et al* 2006). This includes modelling of the lens distortion, usually characterised by four radial lens distortion parameters (k1, k2, k3, k4) and two decentring lens distortion parameters (p1, p2), as well as determination of the principal distance (equivalent to the calibrated focal length, which is the distance between the image plane and the perspective centre) and principal point offset. As stated in Collinearity, the 2D image coordinate system has its origin at the centre of the image. The principal point is the orthogonal projection of the projection centre on the sensor, and is not necessarily the same as the centre of the image, hence the necessary computation of principal point offset values. In a traditional photogrammetric approach these values would be derived through the process of camera calibration, using a test field with objects of known position to model the lens distortion. Calibration is discussed in more detail below (section 2.1.1). In order to compute these values correctly, it is essential that the original image is not cropped.

The interior orientation describes the parameters required to allow the principles of collinearity to be applied to distorted images. The exterior orientation (also referred to as camera extrinsics) describes the position (for example *x*, *y*, *z*) and attitude (roll, pitch and yaw, or omega, phi and kappa) of the camera's projection centre when the image was taken.

The SfM approach, used, for example, by Bundler, Agisoft Photoscan, Photomodeler and Pix4D mapper software, performs an automatic calibration using, in the case of digital images, some of the exchangeable image file format (EXIF) metadata in the image file as a starting point. This defines the camera's interior orientation and simultaneously calculates the exterior orientations using tie points identified on the input images in a process known as bundle adjustment (a reference to the bundles of light rays converging on the optical centre of each camera). This process seeks to minimise the re-projection errors between observed and predicted image points. Unless a pre-calibrated camera model is used, it does this for every image (or camera model) where the settings have changed, allowing increased freedom in image capture beyond traditional photogrammetric processes, such as the use of zoom lenses and uncalibrated camera setups. In these situations, camera calibration is undertaken by the software 'on the fly'.

The resulting 'model' will be in an arbitrary coordinate frame and at an arbitrary scale if no formal control is available. If accurate control measurements are available (measured points rather than those generated automatically), they can be used to orientate and scale the output, as well as provide refinements to the computed positions of the cameras and a check on the overall accuracy of the model.

1.5 The SfM–MVS photogrammetric process

Now that some of the underlying principles have been laid out, a slightly more detailed summary of the steps in the SfM–MVS photogrammetric process is given.

The SfM part of the process generates a sparse point cloud comprising tie points identified and matched across the input images. Other products include the interior and exterior orientations for each camera, but these are rarely revisited by the end-user in most workflows. In order to construct the sparse point cloud, several steps are involved.

Once images have been acquired and imported, the first step is the identification of features, or interest points (IPs), on the images (see Figure 3 for an example). The main requirement is that the definition of IPs should have good repeatability: the same IPs should be detectable across images under different lighting conditions and with different levels of image noise (Hartley and Zisserman 2003), a quality known as invariance. There are several algorithms that can achieve this, for example the scale invariant feature transform (SIFT; Lowe 2004), which is well known among photogrammetric developers. In addition to the IPs, a similarly robust descriptor for each IP is also required, which describes a small area of pixels around each IP, to facilitate matching.
Many IP detection algorithms generate this descriptor at the same time as the identification of the IPs themselves. The number of IPs identified on each image is often set by the user; the default value in Agisoft Photoscan, for example, is 40,000 per image.

Next, the IPs are matched across the different images. False matches are filtered out using an outlier detection algorithm such as RANdom SAmple Consensus (RANSAC; Fischer and Bolles 1981). Some software allows sub-selection of only the best matches for each image. Once a robust set of IPs has been identified and matched across image pairs, the SfM algorithm needs to estimate the interior and exterior orientations for each image by combining all the relative orientations of the image pairs in the form of their fundamental matrices (Verhoeven *et al* 2013). Once complete, a technique called image triangulation is used to calculate the relative position and orientation for each image in every pair. The overlapping pairs are then combined to form a single block, the optimisation of which is achieved by a bundle adjustment (see section 1.4 Interior and exterior orientation), so called because it necessitates adjusting the bundles of rays between each camera's projection centre and the set of projected 3D points until there is minimal discrepancy between the positions of the observed and re-projected points (the image distance between the initial estimated position of a point and its 'true' or measured value) (Verhoeven *et al* 2013).

In Agisoft Photoscan, for example, the IPs are termed key points. Tie points (the sparse cloud points seen in the model view after alignment) are IPs (key points) that have at least two projections each: they are key points that have been matched on two or more images and therefore have become potential tie points. When a tie point limit is used, the software will use only the most reliable tie points on each image to fit the threshold set by the user (for example the top 1,000 per image), which will result in a lower number of sparse cloud points chosen from only the most reliable matches. Using very high IP and tie point limits is rarely productive: it will result in longer processing times and can also affect the accuracy of the alignment because less reliable IPs might be used in the matching process, resulting in less accurate tie points being selected.

The result of all this is a scale- and orientation-free initial reconstruction. If a minimum of three control points (see section 2.3 Control) are introduced and used as constraints in the bundle adjustment, they can be used to reduce further errors in the reconstruction (such as the 'dishing' or 'bowl' effect sometimes seen as a result of processing strips of aerial imagery; (see section 1.8 General workflow) and will also define a coordinate reference system for the model. In some software this is not possible, but Agisoft Photoscan and Pix4D mapper, for example, do permit it. For accurate reconstructions, it is better to integrate the control measurements during reconstruction than to follow the SfM–MVS workflow through to completion, produce the model independently and attempt to define a coordinate system afterwards, as no refinement to the reconstruction parameters is possible at that stage.

Once the SfM part of the process is complete, the dense MVS reconstruction can be undertaken. Now that the optical characteristics of the cameras and relative positions of the images are established, all possible IPs in each image, including those with poorer repeatability than the IPs used at the SfM stage, are calculated to form a dense point cloud, which is similar in appearance to that generated by a terrestrial 3D laser scanner. There are many algorithms available to do this, and different software will use different implementations. The dense point cloud can then be used as the basis of a triangulated irregular network (TIN) or mesh, onto which textures generated from the input images can be projected. The TIN can also be used to generate a raster grid output suitable for use in a GIS.

1.6 Measurement from single, paired or multiple images

This guidance is principally concerned with the use of multiple overlapping images as opposed to single images or stereo pairs. However, it is important to recognise that using many images will not necessarily increase survey reliability and can be surplus to the requirements of the product, so it is often useful to consider the options of using fewer images as outlined in the sections on Single image (1.6.1 below) and Stereo pair (section 1.6.2). Further guidance on these techniques can be found in other Historic England/English Heritage documents (for example *Measured and Drawn*; see section 2 General considerations).

1.6.1 Single image

One of the simplest ways to get measured information from a single image is by using a process known as image rectification. As this guidance is dealing with photogrammetric processing, only an outline description of image

Figure 10
Stages of single image rectification.

rectification will be given here. Rectification involves the projective transformation of a single tilted image to a plane to remove the tilt displacements, optionally including an estimation of lens distortion parameters. Thus, an image with perspective distortion, as taken by a normal camera without special lenses, is re-projected to remove that distortion as far as possible, and in a plane that is parallel to the object plane.

As rectified photography uses only one image, it is effectively a 2D recording technique and so is most suitable for planar (flat) surfaces. If the subject is three-dimensionally complex, with considerable projections and recessions, or undulating, you should consider using an alternative technique. In single image rectification, any image, even if free of tilt, will exhibit displacements because of topographical relief on the subject. Thus, any feature that is either ‘below’ or ‘above’ the reference plane will be misplaced and at the wrong scale because of the central perspective of the image and relief displacements. The greater the tilt of the photograph relative to the main plane of the surface, the greater the error as a result of this relief displacement (also known as height displacement/distortion when applied to aerial images).

There are several limitations to rectified photography, but in some circumstances it can be an extremely effective and cheap solution. Terrestrially, it is usually most applicable when recording architectural facades, floors or ceilings, and software designed specifically to deal with these circumstances includes FARO’s Photoplan. There are also a number of aerial applications for rectified photography. In this case, if you have access to photogrammetric software, generating an ortho-image from more than one image (if available) is preferable, as it takes account of relief displacement (see section 1.6.2 Stereo pair), although to some extent aerial image rectification software such as Irwin Scollar’s Airphoto and John Haigh’s Aerial use existing height data from other sources to mitigate this. The principles of single-image rectification are shown in Figure 10. In this case, software running inside a CAD package is used to match points in the image to surveyed points, a rectified image produced, and detail traced from it. The smaller the amount of distortion present in the original image, the better the rectification is likely to be.

Images can be rectified to some extent at the point of capture by using rising front/perspective correction/tilt-shift lenses, but these present real problems for photogrammetric processing. These lenses are typically used in architectural photography to remove or reduce the effect of perspective, and in this application are usually of relatively short focal lengths (up to 35mm; Figure 11). The main problem is that the position of the perspective centre is moved relative to the principal point (by a physical offsetting of the lens assembly), and this is extremely difficult to compensate for in the photogrammetric processing of such imagery, given that the offset is typically not recorded in metadata (certainly not in pre-digital imagery taken with such a lens, or with a lens that cannot supply such data fitted to a digital camera). When using historical imagery it can sometimes be difficult to spot whether such a lens has been used, and errors in processing can be significant and the accuracy of the product severely compromised. The use of such imagery for measurement is therefore not recommended; clues in images that these types of lenses have been used include tall buildings that have parallel vertical lines rather than the perspective distortion typical of using a ‘normal’ lens, as seen in Figure 11.

1.6.2 Stereo pair

When two overlapping images are available (a stereo pair), a digital surface model (DSM) can be derived in the overlapping area using the principles of intersection described in section 1.2 The chief ray and the principles of intersection. A typical image arrangement for a stereo pair is shown in Figure 12. Reliable measurements can be taken in the overlapping area between the two images.

A single image rectification aims to remove the tilt from the input image but is reliable only for the parts of the subject that coincide with the rectification plane. The DSM derived from two overlapping images allows the effects of relief displacement and other geometric distortions to be taken into account, so that the resulting ortho-image is free from such distortions and can be used like a map (with aerial images) or a plan/elevation (with terrestrial images), irrespective

Figure 11
Images taken using a ‘normal’ lens (left) and a tilt/shift lens (right) to remove perspective distortion.

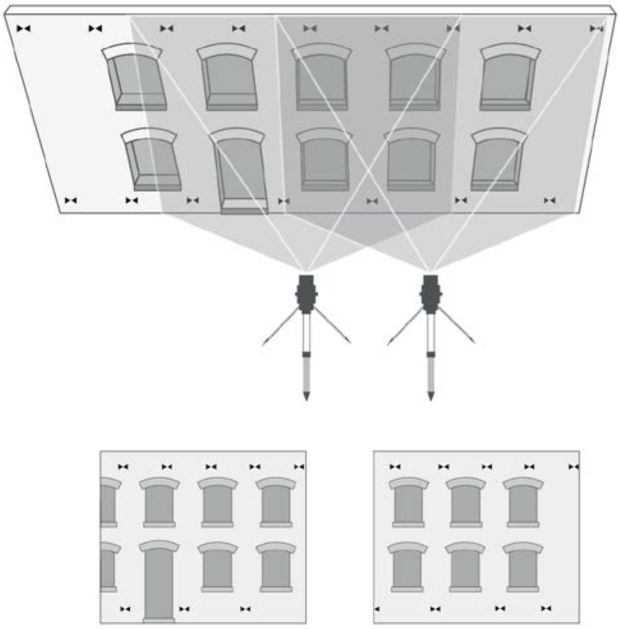


Figure 12
Typical camera configuration for a stereo pair.

rest of the image is still subject to perspective distortion (for example where the buttresses project from the wall face), and these parts of the image are therefore displaced and cannot be used for measurement. In the ortho-image, in contrast, the effects of perspective have been removed and measurements can be taken reliably from any part of the image.

1.6.3 Multiple images

Just as a stereo pair can be used to compute the 3D positions of matched IPs in the overlapping area, in current photogrammetric software many images can be used. In most cases a single stereo pair will not provide the coverage necessary to allow reconstruction of the entire subject. Under these circumstances more images are required, and nowadays photogrammetry is no longer restricted to the former stereo pair constraint of parallelism of the input images. Oblique (both horizontally and vertically) and convergent images can be used as well as parallel images, and this provides a number of additional benefits. A convergent image configuration minimises the systematic errors caused by inaccurate estimation of lens distortion characteristics (Chandler 2010; Wackrow *et al* 2008) and can also provide 100 per cent overlap of image pairs if required, thus permitting more efficient subject coverage and allowing useful images to be taken in situations where ‘normal’ stereo photography would be difficult to apply. Regarding aerial images, current photogrammetric software permits the use of oblique images from flights that circle the subject, rather than flying in the more typical overlapping swaths used for aerial mapping; the addition of oblique images to a typical vertical set can significantly increase the accuracy of the results (Nocerino *et al* 2013; Wackrow *et al* 2008).

Figure 13
Comparison of a rectified image (left) and an ortho-image (right) of the same subject. The rectified area is shown with dashed line.

When using digital cameras, extra images can be taken with ease to increase data redundancy while simultaneously strengthening the geometric configuration. Figure 14 shows the difference between stereo pairs and a highly convergent set of images.

When dealing with multiple images, the bundle adjustment process, as described in section 1.4 Interior and exterior orientation, is used to optimise the 3D reconstruction and refine the interior and exterior orientations such that re-projection errors across the whole model are minimised. When the 3D positions of the tie points are estimated, those points are re-projected onto the images: the difference between the detected and re-projected point position on an image is the re-projection error, and is dependent on both the quality of the camera calibration estimates and (in the case of manually marked points) the accuracy of the marking. It thus provides a good indication of the accuracy or otherwise of the reconstruction.

1.7 Sources of error

There are two main sources of error in photogrammetric processing that can be compensated for. You need to be aware of both.

1.7.1 Systematic errors

These can be caused in a variety of ways, but are mainly concerned with factors that affect the interior orientation. They include the following.

1.7.1.1 Sensors

- Non-planar sensors
- Physical errors in the pixel geometry of the sensor
- Non-perpendicularity between the plane of the sensor and the lens axis

1.7.1.2 Other

- Incorrect lens distortion estimates
- Incorrect positioning of the principal point
- Refraction

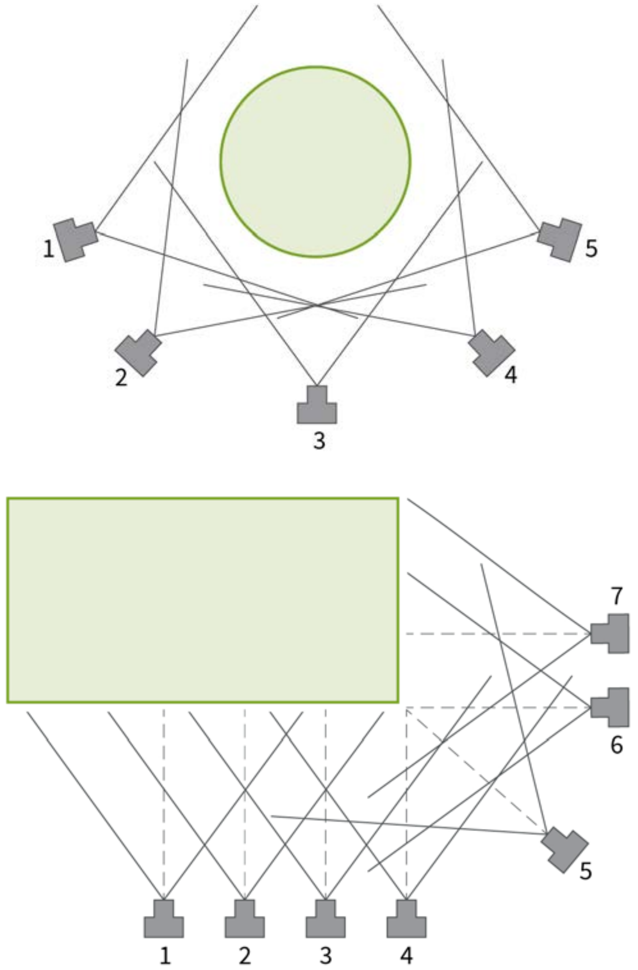


Figure 14
Convergent (top) and ‘normal’ (bottom) stereo case.

Problems with sensors are more difficult to quantify and correct but can, in some circumstances, be helped by calibration (Fryer *et al* 2007). In most digital cameras, planarity of the sensor can be safely assumed; incorrect interior orientation parameters can be resolved during bundle adjustment, and these can also be improved to some extent by calibration.

1.7.2 Mistakes

Mistakes usually involve either incorrect matching of points during automated alignment or the incorrect identification and/or measurement of control points. In the former case adjustment can be repeated after manually orientating the problem images, while in the latter case the misidentification can usually be found quickly and rectified.

1.8 General workflow

The general workflow for SfM photogrammetric processing is outlined here. At all stages metadata is important; some of this will be generated automatically by the software employed (including processing and accuracy reports, if available), while other elements should be generated by those working on the project.

- Planning
- Reconnaissance
- Image acquisition
- Image pre-processing
- Image import
- SfM, calculation of interior and exterior orientation, identification of IPs across the image set, formation of sparse point cloud based on those IPs
- Incorporation of control data, alignment optimisation
- MVS, formation of dense point cloud by parsing all images and projecting most of the pixel data contained in them as 3D points, provided they can be matched and identified in at least two of the input images
- Dense point cloud editing (optional)
- Generation of other outputs (high-resolution mesh, ortho-images, DEMs, etc)
- Further processing and analysis of those outputs in other software (CAD, GIS, etc)
- Presentation
- Archive

Figure 15 shows the basic elements of a close-range photogrammetric workflow in graphical form. At all stages there are several possible refinements to the process, many of which will increase the likelihood of generating accurate outputs with verifiably good metric performance. The order in which some parts of the workflow have to be undertaken can vary depending on the software being used, as do the refinement options available.

All images should be checked before passing them through the workflow, primarily to remove those that are of poor quality, usually those that are comprehensively out of focus or exhibit significant motion blur as a result of either incorrect camera settings or the use of frames grabbed from video. Some software has image quality assessment functionality; none of their methods are perfect, however, and a visual inspection of the inputs is always advised before processing starts. Individual images that cannot be correctly aligned can be removed, provided there is sufficient redundancy in the inputs, or can be manually aligned with the introduction of local image control points. Additionally, problematic areas of images can, in some software, be masked to remove features that do not need to be reconstructed, for example sky, logos, fiducial marks or moving elements in a scene. This can save a considerable amount of time later in the process.

Sparse point clouds can, in various software, be filtered to remove points with high re-projection errors or reconstruction uncertainty. In general, the Root Mean Square Error (RMSE) of the re-projection errors should be below 1 pixel; the smaller the value, the better the accuracy of the reconstruction. Although filtering for re-projection errors is an iterative process, you should not carry out the filtering step more than three times, as this can introduce a ‘stepping’ effect into the model (Figure 16). You should also avoid removing too many points during filtering, as reconstruction can then become compromised or impossible. If the input images are producing very large re-projection errors that cannot be mitigated, it is likely that they are either of poor quality or the camera calibration parameters cannot be accurately determined.

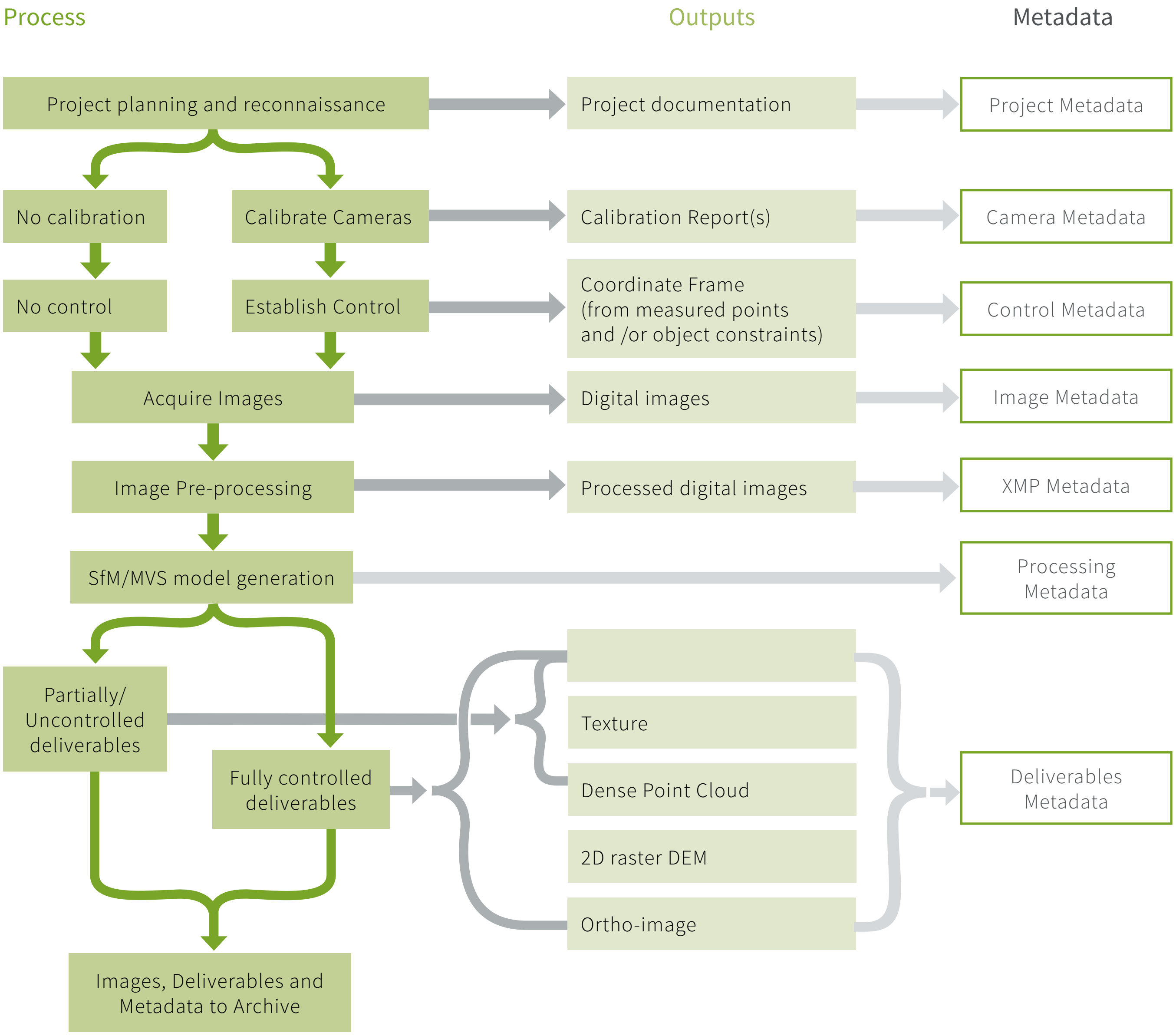


Figure 15
Basic elements of the photogrammetric workflow.

In cases where coordinated control point data is available, the whole process can be refined, for example in Agisoft Photoscan Pro, by building a low-accuracy dense point cloud and a low-resolution mesh (in order to enable semi-automated placement of control); after carefully positioning all control points and assigning their coordinates, optimisation of the image alignment can be carried out using those values. This mitigates the effects of inaccurate camera calibration estimates and also greatly increases the accuracy of the reconstruction, depending in part, of course, on the accuracy of the control measurements. The newly refined alignment can then be used as a basis for re-initiating the next stages of the workflow, as the previously generated dense cloud and mesh will have been rendered redundant and removed.

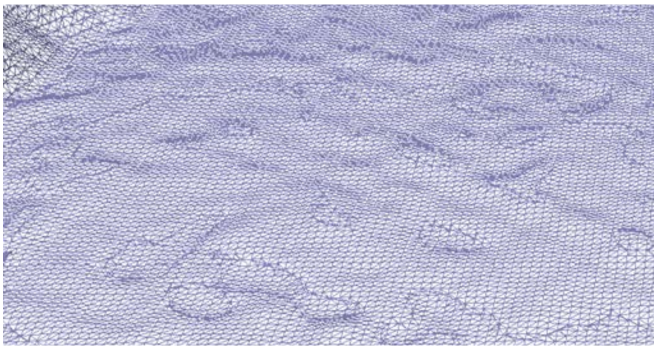


Figure 16
Over-use of filtering, leading to a pronounced 'stepping' effect in the mesh.

In Figure 17, the 'bowl' effect is caused by inaccurate initial camera calibration estimates at the image alignment stage. This can be mediated by either loading the correct camera calibration values before alignment (if a calibrated camera system is used) or by using ground control points (GCPs); the software will then take into account the additional constraints introduced by the GCPs when the alignment is optimised. The use of GCPs to increase reconstruction accuracy is recommended even if a calibrated camera is used.

Figure 17
'Bowl' effect caused by inaccurate initial camera calibration estimates. The problem is not immediately visible in plan (top), but the side view (bottom) shows the effect.

Software

Software available for structure from motion (SfM)/multi-view stereo (MVS) processing can be grouped in many ways: here it is divided by cost into free and commercial packages. A useful comparison of the metric performance of a variety of these packages using the same data is given in Remondino *et al* (2012). It should be noted that this is a rapidly developing and expanding market: any references given here are likely to be superseded extremely rapidly, as new companies move into the area from a wide variety of commercial perspectives and applications. It should also be noted that this section is in no way an endorsement of any of the packages described, but a summary of some of the more popular software currently (2017) being used in the archaeological sector in the UK.

Free solutions are generally either released under the GNU public license, such as Bundler, PMVS2 and the GUI 'wrapper' for them, Visual SfM (Wu 2011), or offer cloud-based solutions using a system where the user uploads photographs that are processed and the model returned, such as KU Leuven's Arc3D and many others. These are discussed in more detail below.

Open-source software

There are many advantages to using open-source software, among them cost, development options through access to the source code and ownership of data and format (Green *et al* 2014). However, using this system, getting from the starting material (the images) to products [digital elevation models (DEMs), ortho-images, etc] requires the use of several different pieces of software at different stages (Green *et al* 2014).

The freely available desktop solutions, of which perhaps the most user-friendly is Visual SfM, do not generally allow the use of formal control in the processing of the data, and furthermore do not allow optimisation of image alignment based on control data. Instead, the SfM sparse point cloud is built, the dense cloud then constructed, and this product (or a mesh derived from it) positioned using an affine transformation incorporating the control points surveyed in the field. This can be achieved in other open-source software, such as Cloud Compare or Meshlab. In many cases this does not present any difficulties, but serious problems can be encountered, especially when working over large areas, if working with projected coordinate systems [that is those gathered using global navigation satellite systems (GNSS) systems, or a total station theodolite (TST) when using a scale factor of anything other than 1], as a degree of distortion is introduced into the control measurements that cannot be compensated for unless the software is capable of dealing with projected data. The net result of this is that the control measurements cannot be used properly, and the results will not align well with data derived from other sources or when overlain on, for example, an Ordnance Survey map in a geographic information systems (GIS) or computer-aided design (CAD) system.

Reliance on the SfM process alone can also generate errors in some data sets (for example the bowl effect shown in Figure 17). These can be compensated for to some degree by using calibrated cameras, but the best way to fix them is to optimise the alignment based on either accurate camera or ground control point (GCP) coordinates. Without the ability to incorporate control measurements into the SfM/MVS workflow at the time of model creation, these types of errors cannot be mitigated by most open-source solutions at the time of writing, although the functionality is found in many commercial packages.

One potential advantage of the Bundler/PMVS2 workflow is that it involves processing all of the data on a local machine. This means that the process can be controlled by the end-user, and elements of the workflow changed according to the requirements of the job at hand. A potential disadvantage, however, of all systems (free or commercial) that manage the data locally is that large data sets can take a very long time to process, depending on the hardware available. The SfM/MVS workflow is computationally intensive, especially with large numbers of high resolution inputs. It is often difficult to process effectively on a laptop, for example, where resources are typically insufficient to obtain good results in a reasonable timeframe unless few, or relatively low resolution, images are used. One potential solution to this problem is cloud processing, using many fast computers elsewhere to perform the 'heavy lifting' parts of the operation, and to evaluate and analyse the end results locally.

Free cloud-processing solutions

Such solutions include Autodesk's Recap Image or Recap 360, although both also offer versions with more functionality at a cost, and KU Leuven's Arc3D, that are all useful for cloud-based 3D reconstruction. They do not down-sample images, and the models produced, although still arbitrarily scaled and orientated, have relatively good metric performance and are beautifully textured. In many situations the product compares very favourably with that generated using commercial packages.

It is also important to note that copyright of some of the results from cloud-based free software may reside with the software provider and is in many cases not licenced for use in a commercial context.

Commercial packages

There are many commercial photogrammetric packages available, at a range of prices. Outside academic institutions, however, relatively few of the more expensive solutions (for example BAE Systems' Socet Set or Hexagon's Erdas Imagine) are used in UK archaeology, so the focus here is on the less expensive end of the market. Some solutions focus almost entirely on the aerial survey sector as their primary goal (such as SimActive's Correlator 3D; although these are not cheap, the potential return on the investment is good if they are being used in a commercial environment on a regular basis. More versatile solutions include the ability to work with terrestrial imagery as well as aerial imagery, deal with highly convergent image sets, and produce full 3D models from a variety of inputs. The most popular include Agisoft Photoscan, Pix4D mapper, 3DF Zephyr and RealityCapture; the latter additionally allows the direct integration of data derived from both photogrammetry and 3D laser scanning. Different licensing models are sometimes available (for instance, licenses for Pix4D mapper may be rented for a monthly or annual period in lieu of an outright purchase, and RealityCapture currently offers a rolling license model that is considerably cheaper than the full purchase price) that can make these solutions more affordable for those on limited budgets. Like the open-source solutions, they allow local processing of data, and therefore increase the amount of control that the surveyor has over the data and the processing workflow as well as integrating external control data. Some, like Pix4D mapper, additionally offer a cloud-processing option for projects, while others, like Agisoft Photoscan Pro, offer the capability for network processing of projects, both solutions going some way to obviating the need for very powerful computing resources in-house.

Commercial cloud-based solutions, such as Drone Deploy, offer end-to end processing solutions that can optionally include flight planning, and which offer processed outputs including 3D models, DEMs, ortho-images and normalised difference vegetation index (NDVI) composite images (if appropriate imagery is uploaded).

2 General Considerations

2.1 Capturing the initial data

In photogrammetry, the quality of the output is almost wholly dependent on the quality of the input. Poor photography will inevitably lead to inaccurate results, so time spent familiarising yourself with the camera you intend to use, and considering the best image configurations for the subject, is seldom wasted. This section will summarise some of the main issues; there are several excellent resources for more detailed expositions of how cameras work and how this is relevant to the photogrammetric process (for example Stylianidis and Remondino 2016, 127–251).

In general, optimal exposure for photogrammetry, as in ‘normal’ photography, involves a balancing act between aperture, shutter speed and sensor sensitivity. The aim is to produce clean, sharp images of the subject. You should aim to use the fastest shutter speed that conditions allow (to reduce the chance of blurring), the lowest ISO setting possible (to reduce image noise) and the optimum aperture to retain sharpness and appropriate depth of field (often between f/8 and f/11) across the subject.

There is no ‘best’ camera for all photogrammetric work, although a single good-quality camera can be a far more versatile sensor in a variety of situations than, for example, a much more expensive 3D laser scanner. Different types of laser scanner perform well at some ranges and tasks but not at others (*3D Laser scanning for heritage*), but a single good-quality camera retains versatility across many photogrammetric scales of operation, in part through the application of different lenses. The use of metric cameras in UK archaeology is not widespread, so their use will not be considered in any detail here.

Broadly speaking, DSLRs will provide better results than compact cameras, and these will in turn provide better results than ultra-compact cameras (Wackrow 2008) or mobile phones, for many reasons as discussed in Capturing the initial data. In some cases, the camera that can be deployed may not be the best from an image quality point of view, but may be necessary because of weight or bulk restrictions, a situation commonly found when using fixed-wing SUAs, kites or masts. In any case, the best quality camera available should be chosen for the job, which is not necessarily the camera offering the highest pixel count. Unless money is no object, you should not buy the newest, or most high-end, camera on the market, as these are normally very expensive and prices usually come down to affordable levels within a year or two. Money is much better spent on good-quality lenses, which often retain usability with newer camera bodies over many ‘generations’.

Some software can process ‘spherical’ imagery taken with, for example, a Spheron VR camera, iStar or other 360 degree imaging systems. While these can provide excellent coverage and overlap in an indoor setting, when used outdoors a large number of the pixels may be imaging sky and ground, reducing considerably the number of effective pixels available for modelling the subject

(Figure 18). Unless using in-camera high dynamic range (HDR) imaging, interior illumination will often be challenging and can limit the usability of lower cost 360 degree cameras.

2.1.1 Calibration

Although much of the photogrammetric software currently in use in archaeology does not require a pre-calibrated camera (with calibrations being calculated for each camera during bundle adjustment), in most cases more accurate results can be obtained using a setup in which the distortion parameters are consistent and measured in advance with a calibrated fixed focal length (prime) lens. Adequate results can be gained from very variable input photography using, for example, a zoom lens on a camera set up to adjust all settings fully automatically for 'optimal' exposure. Much of the time, the software will be able to estimate successfully the interior orientation values for the camera for each exposure with different settings, and to apply these during the reconstruction phase.

The collinearity equations assume that the image point, projection centre and object point are in a straight line, and that the image is formed on a plane. This last assumption is the reason why in the past medium- and large-format metric film cameras often used a partial vacuum to suck the film flat. In modern digital cameras, it is generally assumed that the sensor is planar. Thus the only factors left that can affect output are refraction (as mentioned in section 1.6.1 Single image), not usually an issue in archaeological work) and lens distortion, and it is these lens distortions that the calibration process seeks (in part) to model and mitigate.

A variety of methods are available for camera calibration, ranging from professional 3D test fields (which are beyond the means of most but can be commissioned) to relatively straightforward solutions that usually involve photographing a 2D test image from a variety of angles in order to provide an approximate lens model. In all cases, the aim is to estimate (at a minimum) the radial lens distortion parameters (k1–k4) and decentring lens distortion parameters, also known as tangential distortion (p1, p2), thus enabling a reasonably accurate estimation of the principal distance (calibrated focal length) and the principal point, together providing the interior orientation. Once all of these parameters have been determined, they can be applied to the images in such a way that the idealised

Figure 18
Outdoor use of a spherical camera.

assumptions of the collinearity equation can be used to reconstruct 3D points from 2D inputs when combined with an estimate of the exterior orientation (position and attitude) of the camera. In some very cheap cameras and mobile phones it cannot be assumed that the sensor is in fact perpendicular to the lens axis because it may be glued in place (Bradski and Kaehler 2008), leading to severe distortion. In this case the calibration routine should also take into account skew and different values for F*x* and F*y* (the focal length in *x*- and *y*-dimensions measured in pixels); in Agisoft Photoscan, for example, these coefficients are estimated during camera alignment optimisation (A Pasumansky, pers comm).

Before starting a calibration, settings appropriate for the project should be chosen. The aperture of the lens should be stopped down to give sufficient depth of field: choose the sharpest aperture setting for your lens (usually around f/8), which will vary depending on the requirements of the job, and calibrate using this value. Using calibrated fixed focal length (prime) lenses will involve setting the focusing distance appropriately (typically you might choose to focus at infinity, or perhaps for closer range work at 1m or 2m) and then preventing this from changing (using electrical tape or a locking screw, if available). In Figure 19, the focal length has been set to infinity, and a note of the settings made on the tape. The camera should be set to manual mode, and electronic assists such as auto-focus (AF) and image stabilisation should be switched off, in many modern systems on both the camera and the lens. At this point, the instructions for whatever calibration software you are using should be followed.

Some photogrammetric software is very good at estimating robust interior orientations, and may be better at it than some of the cheaper (or free) calibration software available, although the latter can provide useful starting points for parameter estimations. There is no standard format for camera calibration results, so it can be problematic moving the results from one piece of software into another; photogrammetric software packages typically only allow the import of some results from other packages.

Figure 19
Prime lens taped to focus at 1.2m.

Examples of test fields used by different software packages are shown in Figure 20. Calibration should be re-done if:

- settings have been deliberately changed (for example a new focal length selected)
- settings have been accidentally changed (for example the camera has been dropped, knocked or treated roughly)
- the lens has been removed or replaced

If used, calibration should be undertaken approximately every 12 months, or before starting a major project. With the correct setup, it can be a relatively rapid process.

2.1.2 Resolution and sensor size

The resolution and sensor size of different cameras varies widely, and has a significant impact on the quality of the images produced. Medium- and large-format sensors are not very widely used in UK archaeology, and their use will not be considered here.

Generally, the larger the sensor and, to some extent, the larger the individual pixels on it, the better the image quality will be. You will be able to distinguish and model more detail in a high-resolution image than in a low-resolution image because the same parts of the subject are represented by more pixels in the higher resolution image, assuming the image scales are the same.

Very small sensor arrays with densely packed pixels will generally produce noisier images, and be more likely to exhibit undesirable artefacts and optical effects. DSLRs will usually have larger sensors than compact cameras, which in turn have larger sensors than ultra-compact cameras or mobile phones. Larger sensors come at a price, however. Not only do they cost more, but the cameras housing them are larger, the lenses are generally larger and they weigh considerably more, which means that, for example for use with a SUA, a larger platform is needed to carry them.

Table 1 gives some typical values for a variety of sensor sizes and the cameras that can use them. From this, it can be seen that a compact camera can have a sensor size only 20 per cent that of a 35mm full-frame sensor. If the pixel count matches that of the larger sensor, then the individual photo diodes on the sensor of the compact camera will be much smaller than those in the full-frame camera in order to fit on the smaller sensor. Smaller pixels sacrifice a larger proportional area to secondary circuitry on the sensor and their more limited light-gathering capacity requires additional signal amplification, resulting in higher signal noise. Thus closer pixel spacing on sensors can lead to decreased sharpness, a smaller dynamic range (which can lead to problems with clipped highlights), less colour saturation, increased chromatic aberration and consequently lower overall image quality. As an example, a Nikon D3X with a 24MP full-frame

Sensor name	Dimensions (mm) (approx.)	Area (mm^2) (approx.)	Percentage of 35mm full-frame (approx.)	Typical cameras and approx resolutions (mega-pixels, MP)
35mm full-frame	36×24	864	100	Nikon D3X (24MP), D800 (36MP) Canon EOS 5D mark III (22.3MP) Leica M (24MP) Sony Alpha 7R II (42.4MP)
APS-H	28.7×19.1	548	63.45	Canon EOS 1D (inc. marks II–IV) (8.2MP for mark II)
APS-C (Nikon DX)	23.6×15.7	370	43	Nikon D300 (12.3MP), D3000 (10.2MP), D7100 (24.1MP), D80 (10.2MP), D70 (6.1MP)
APS-C (Canon)	22.2×14.8	329	38	Canon EOS 7D (20.2MP), EOS 60D (18MP), EOS 50D (15.1MP)
4/3”	17.8×10	178	20.6	Panasonic Lumix DMC-L10 (10MP) Olympus E5 (12.3MP) Leica Digilux 3 (7.5MP)
1/1.7”	7.6×5.7	43	5	Canon Powershot G12 (10MP) Ricoh GR (16.2MP) Nikon Coolpix P7100 (10MP) Panasonic DMC-LX5 (10MP)
1/2.3”	6.2x4.6	28	3.25	Sony Cybershot DSC HX50

Table 1
Typical values for sensor sizes.

sensor has a pixel area of 35.05µm^2 and a pixel pitch (size) of 5.92µm, whereas a Sony Cybershot DSC HX50 with a 20.4MP 1/2.3” sensor has a pixel area of 1.39µm^2 and a pixel pitch of only 1.18µm.

As new cameras and sensors are released at a rapid rate, the data in Table 1 will quickly become out of date, but the principle being demonstrated will remain relevant.

You can typically expect poorer results when using cheap equipment and it is often a false economy to do so. While it is acknowledged that the imagery from very light ‘hobbyist’ SUA configurations will process, the metric quality of the results, as well as the resolution of fine detail, is very often at the edges of what is considered acceptable, as only cameras that are light enough can be carried on such platforms. Some cameras in this category, notably those primarily designed for sports and recreational use (being helmet or handlebar mounted), exhibit high degrees of image distortion (Figure 21; in this case made clearer by the horizon line), considerable chromatic aberration in certain light conditions, and were certainly not designed with photogrammetric outputs in mind. That said, some software manufacturers are building in the capability to deal with imagery derived from such cameras, given their popularity, robustness and light weight.

2.1.3 Focus and sharpness

The sharper the image, the better it is for photogrammetry, although there are caveats about processing images to increase sharpness (see section 2.1.10 Image enhancement). Sharpness should be a result of good-quality lenses and optimal exposure rather than image enhancement. Focus is equally important: out-of-focus shots will process very poorly, and can lead to serious errors being introduced into a data set. It is well worth spending time checking your images before running them through the photogrammetric process. AF lenses in an uncalibrated setup can sometimes be problematic in this regard, and you should check whether the correct focus point has been selected, and adjust it (by switching the lens to manual focusing, for example) if necessary. If you are

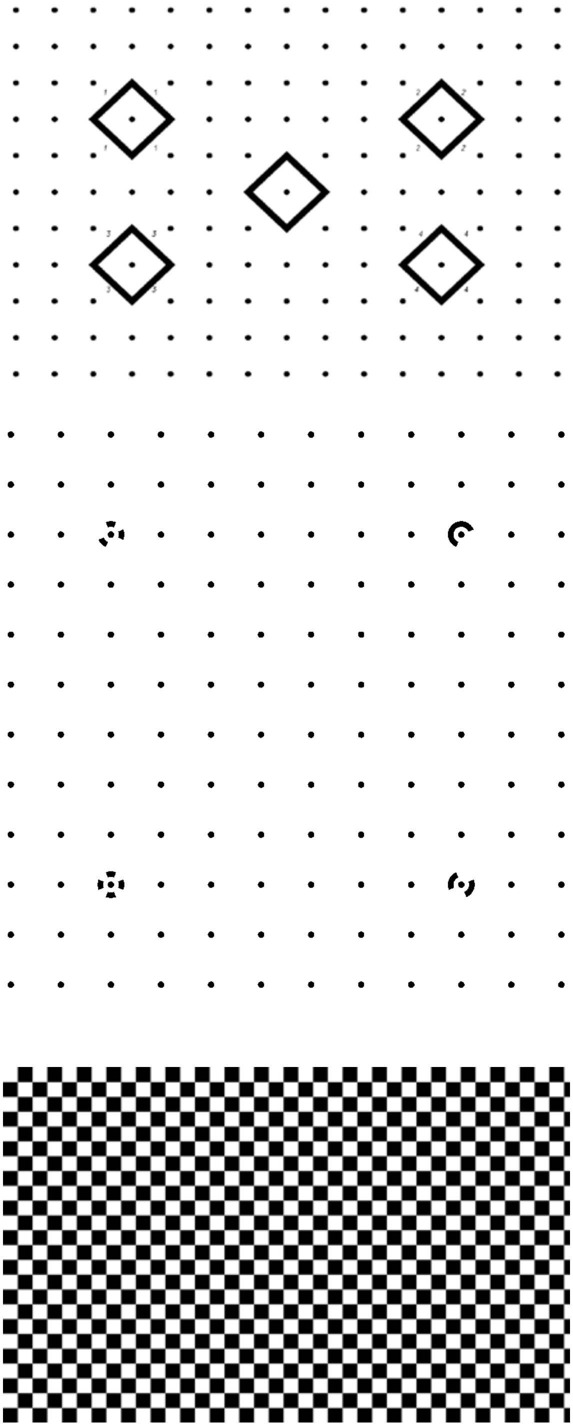


Figure 20
Examples of different camera calibration images.

Figure 21
Severe image distortion from a recreational camera.
© Skyline images

using a calibrated lens, the focus will remain fixed and any AF functions must be turned off. This is particularly important if you are shooting under circumstances that will be difficult to replicate, or at a site where access is limited and a return visit will be problematic. Some photogrammetric processing software permits the masking of areas of images that are out of focus before processing begins, and if possible this option should be used. Although resolution has a bearing on the quality of information that can be gained, it should be realised that poor-quality lenses will yield results that lack sharpness whatever the resolution of the camera used. Depending on the subject being imaged, the area of the image that is in focus is heavily influenced by depth of field.

2.1.4 Depth of field

Depth of field is controlled by the aperture settings. The aperture is a hole of variable size that controls how much light is let into the camera during an exposure. A camera is only able to focus its lens at a single point, but there will be an area that stretches in front of and behind this point that still appears sharp. This sharp area represents the depth of field and is not a fixed distance, as it is controlled by the size of the aperture. It can be described as ‘shallow’, where only a small zone around the focus point appears sharp, or ‘deep’, where a larger proportion of the image appears sharp. Larger apertures (smaller f/ numbers) lead to a shallower depth of field, whereas smaller apertures give a deeper depth of field (Figure 22). This can sometimes present problems when shooting in low light conditions where a larger aperture is desirable, especially when a tripod cannot be used to allow longer exposures to compensate. In these situations, increasing the sensor sensitivity (ISO values) is often the only other option. Most lenses have an optimum aperture setting for minimising lens distortion, usually between f/8 and f/11, but the depth of field will increase across the whole range of apertures. If you are photographing largely flat surfaces this does not present much of a problem: use whatever works best under the circumstances, and much wider apertures can be safely used, with the additional benefit that ISO values can be reduced, resulting in less noisy images. It is sometimes the case, however, that you need to increase the depth of field (to keep more of the image sharp) by decreasing the aperture to, say, f/16 or smaller, in which case you will almost certainly need to use a tripod to compensate for the correspondingly longer exposures necessary, especially in poor light.

Depth of field becomes increasingly important the more ‘3D’ the subject is, or the more oblique the images of the subject are: anything that is not in focus usually has to be masked from the input photographs or they cannot be processed accurately. This is less of an issue in high-level vertical aerial photography, where the ground surface is relatively planar compared with the camera under most circumstances, but becomes more of an issue with lower level SUA or kite photography, especially when that is oblique, and can have a serious impact on some terrestrial projects (Figure 23). It can also present difficulties when using lenses that have very narrow depth of field characteristics (such as section 3.4.1 Macro lenses). Ultimately, you need to ensure that you have as much of the subject as possible in focus when the exposures are made.

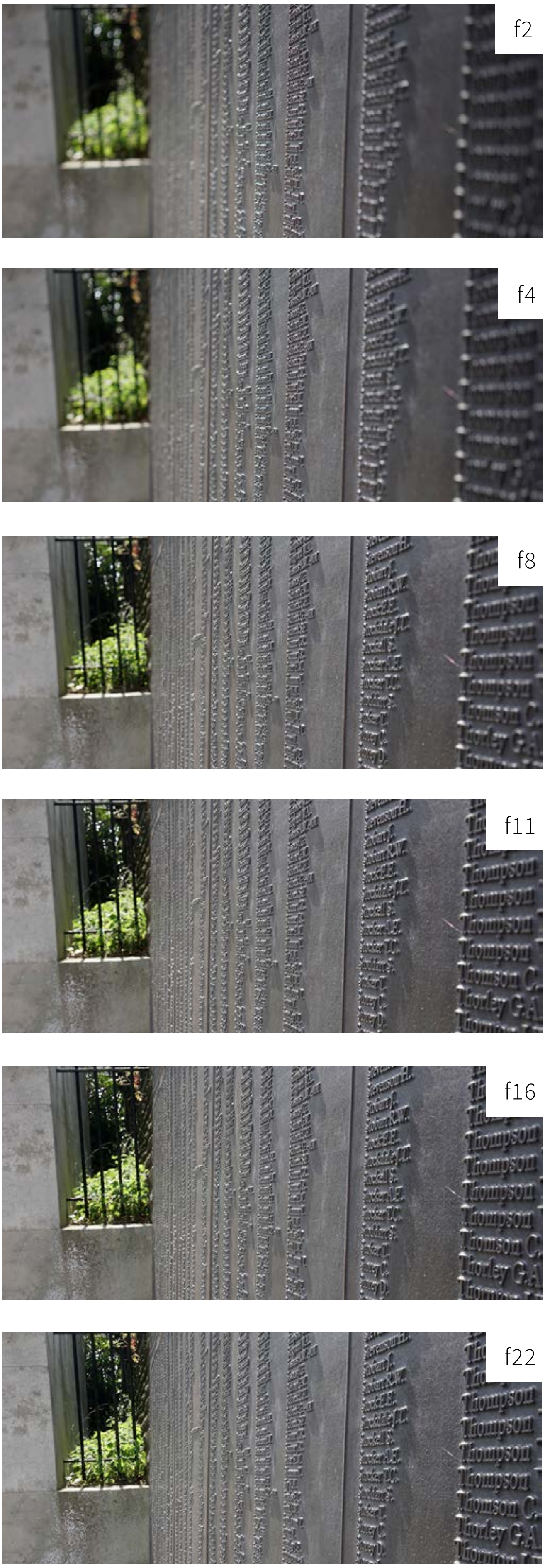


Figure 22
Different aperture settings showing the effect on depth of field.

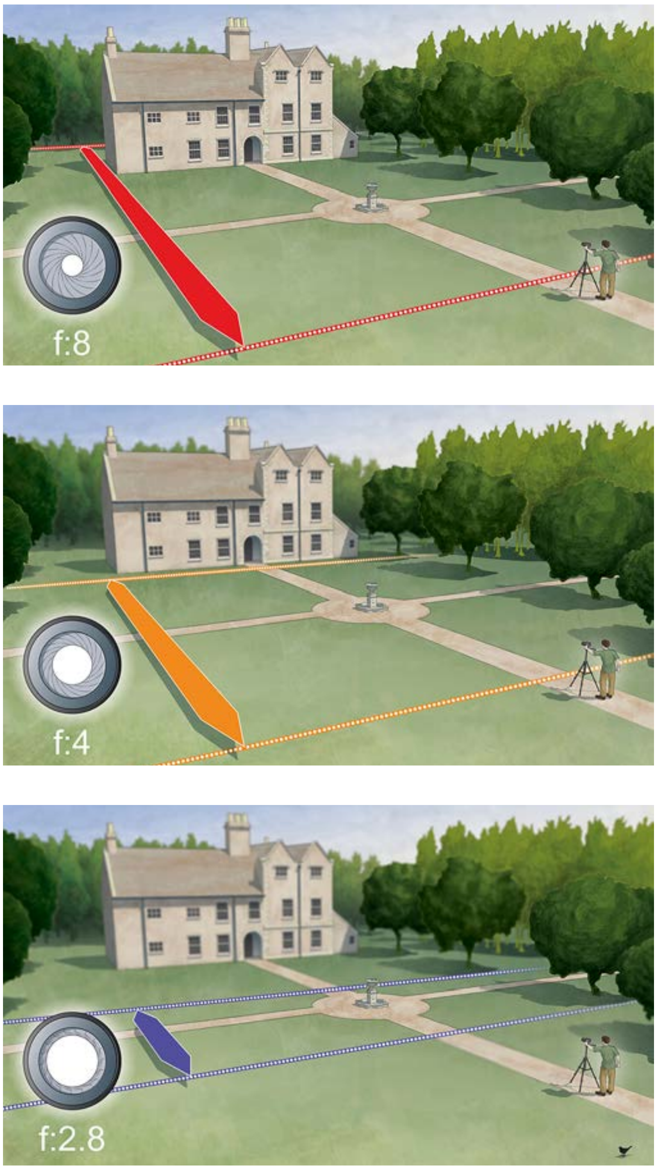


Figure 23
Depth of field in an applied case.

2.1.5 Film speed and sensor sensitivity (ISO)

ISO values (the approximate equivalent of ASA film speed when using an analogue camera) reflect the relative sensitivity of the sensor to light (Figure 24). In general, ISO values should be kept as low as possible to reduce noise in the image. Increased noise at high ISO values is a well-known phenomenon, especially in older digital cameras, and can lead to significant degradation of the derived products.

In certain circumstances, for example when shooting from a mobile aerial platform, hand-held device or in high winds, faster shutter speeds are essential to avoid motion blur and to retain sharpness in the outputs. In these conditions, apertures will often have to be opened up (lower f/ numbers selected) to allow more light to reach the sensor during the exposure, and ISO values may need to be set higher to result in a properly exposed image. In these situations, ‘fast’ lenses (those that permit wider apertures to be used) are helpful, as they are in low light conditions, but wider apertures are used at the expense of depth of field.

When a stable platform (for example a tripod) is available, smaller apertures and lower ISO values can be used to ensure adequate depth of field across the subject and a minimum of image noise. Most cameras have the functionality to use either shutter priority or aperture priority. In the former case, the user sets the desired shutter speed and the camera adjusts the ISO and aperture values to gain an optimal exposure, and in the latter the user sets the desired aperture and the camera adjusts the ISO values and shutter speeds accordingly. Adjusting aperture is not an option if a calibrated lens is being used. If you are using a tripod in low-light conditions it is possible on many DSLRs to use a mirror lock-up mode, which further reduces the chances of camera shake during a longer exposure, especially when combined with a delay timer or wireless remote trigger. Mirrorless cameras can be used to mitigate this problem, and in some cases offer an electronic front and rear curtain to avoid any movement during the exposure process.

Figure 24
Effects of different ISO settings. Shutter speed and aperture are constant throughout.

The use of external lighting rigs is advised if possible, especially in low-light indoor conditions, to allow clean exposures in otherwise trying conditions. If cameras rely on a fully automatic setting, they often choose exposure settings that could have been improved by manual intervention, as in the aerial example shown in Figure 25. In this instance, the shoot was taken on an overcast and very windy day, with a compact camera on full automatic settings (necessitated by the firmware on the SUA platform being used). To compensate for low light and the high shutter speed necessary to avoid blurring (1/2000s), the aperture was opened wide (f/2) and ISO values increased to 1600, resulting in considerable noise in the final image, which in turn led to low-quality results. When re-flown with a better camera on a more stable platform, there was significant improvement in the imagery (Figure 26).

In general, ISO values should be kept as low as is practically possible under the circumstances, although some newer cameras are capable of shooting very clean images even at high ISO values. Where previously, and still if using older cameras, the advice was to stick to ISO 400 or below, it is now possible, if circumstances dictate, with many modern cameras, to use much higher values with relatively little image noise penalty.

2.1.6 Lighting

In contrast to ‘normal’ photography, relatively flat lighting is generally preferred for photogrammetric purposes. Typically, lighting is used to emphasise texture; for aerial archaeological photography, images are often taken primarily to emphasise features on the ground, with the sun at a low angle; for architectural photography, images are taken to elucidate details on a building or structure. Areas hidden in deep shadow may not yield the best photogrammetric reconstruction results, and overexposed areas can have a negative effect on the outputs. If ortho-images or model textures are part of the desired output, it is best to try to avoid significant changes in ambient lighting conditions during a shoot. Although the metric properties of the output should not be affected too badly (on the understanding that exposures are not heavily compromised by changes, for example, with a good deal of over- or underexposure), the quality of blended textures and computed pixel values for the output points may be adversely affected. There are ways round this when the changes are relatively small (for example Agisoft Photoscan offers average, minimum and maximum options for texture generation in addition to the normal blending modes and a facility for colour correction, although this can incur a significant time penalty, especially when processing large numbers of images).

Figure 25 (top)
High ISO values producing noise in an aerial image taken with a relatively cheap camera from a fixed-wing SUA.

Figure 26 (above)
The same area re-imaged with a better full-frame mirrorless camera mounted on a multi-rotor setup.

Try to avoid using the in-built flash on a camera, as it is highly directional and the lighting on the subject therefore changes dramatically between exposures. It is far better to use ambient light, or if possible to light a scene or subject using external lighting rigs (Figure 27), to maintain a constant light over the scene during capture. A mast can be seen to the right of the image in Figure 27: this was used to get images perpendicular to the wall paintings in addition to the shots from the tripod. If using external lighting sources, attempt to light the scene as evenly as possible and try to avoid pockets of deep shadow or highlights on the subject. Some LED lighting rigs allow you to alter the colour temperature as well as the intensity of the light during a shoot. If colour reproduction is important (as it nearly always is in photogrammetric projects), colour reference cards should be used (Figure 28) and camera white balance settings adjusted according to the prevailing conditions, Most cameras offer the option of setting a custom white balance and this should be used when the accurate rendition of colour is important.

Figure 27
Lighting rig in use while photographing wall paintings.

2.1.7 Lenses

Better results will be obtained by using better quality lenses. Even on a high-quality camera, poor lenses will yield images that lack sharpness and clarity. Cheap lenses are almost always a false economy for accurate photogrammetry, although it is acknowledged that results can be obtained using even a mobile phone camera.

DSLRs or compact systems that allow interchangeable lenses are generally more versatile than other options, albeit at a higher price. If you are using a point-and-shoot camera, try to get one with the highest quality lens that you can afford.

For photogrammetric work, it is generally best to avoid using image stabilisation (IS) or vibration reduction (VR) functions on lenses or cameras that offer this capability. Although the images produced will appear sharper, systems of this sort generally work by moving either the image sensor itself or an optical element group in the lens at or immediately prior to the point of image capture, both of which result in a slightly offset principal point, although this offset can be estimated during the SfM process.

The best results are obtained using fixed focal length lenses, especially if these have been calibrated. Wide-angle lenses (for example around 28mm) can be very useful for capturing as much of the subject as possible without introducing too much distortion, reducing the number of images required and improving matches between images (Figure 29). As can be seen, the longer the focal length, the narrower the field of view becomes, although the magnification factor increases. Some software allows the processing of images taken with very wide-angle or fish-eye lenses, up to, for example, 12mm (35mm equivalent), but their use should generally be avoided, at least in part because the resolution can vary considerably across the image and radial distortion is high. Zoom lenses can be employed, and there will be situations when their use is unavoidable. Provided the approximate focal length values are written to the image EXIF data this is not usually a problem, and even without this information most software currently available is extremely good at estimating the focal length. Zoom lenses have the additional benefit of providing a great deal of flexibility for the photographer.

Figure 28
Example of a colour calibration chart in use.

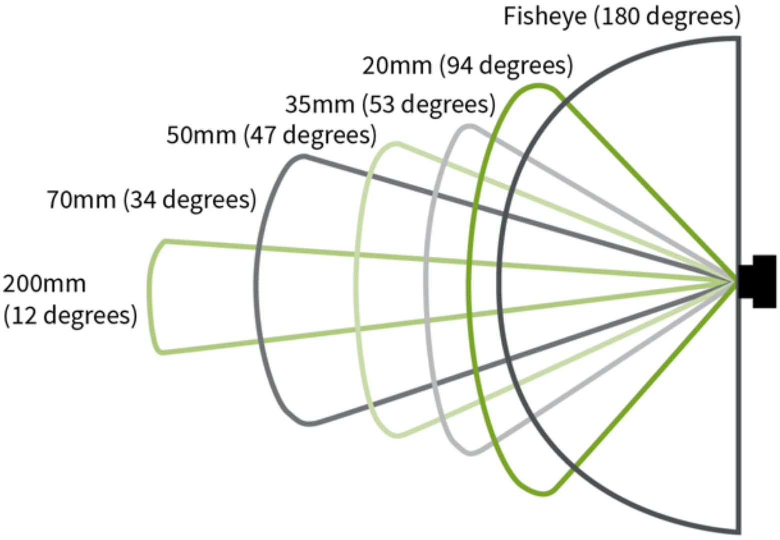


Figure 29
Fields of view achieved by different focal lengths of lens.

When imaging very small objects, macro lenses can be used. These usually offer a very shallow depth of field, so it may be necessary to use a very small aperture to compensate for this and allow more of the image to be in focus (see section 3.4.1 Macro lenses).

2.1.8 Image format

Almost all digital cameras on the market today are capable of saving images in joint photographic experts group (JPEG or JPG) format. Some, notably those at the lower end of the market, such as compact cameras, will only output images in this format. Other cameras allow the raw data from the sensor to be output in RAW (not an acronym) format, and some also allow the data to be saved as tagged image file format (TIFF) files.

RAW files are minimally processed by the camera, their generation involving simply the conversion of the analogue information gathered by the sensor to a digital format with some amplification, and thus they constitute the 'digital negative'. Although all digital cameras record in RAW at the moment of capture, in cheaper cameras this RAW file is converted to JPEG immediately and the raw information discarded. In this case, the user or automatic settings (for example white balance, sharpening and exposure adjustments) are applied to the raw data when the file is written, and a clipped tonal curve is also applied. Once the file is written, these changes cannot be undone.

The RAW format, in contrast, allows the image to be altered post-capture without affecting the original data. A RAW file contains information in three main groups: data numbers (DNs), describing the intensity of signal received by each photo-diode (pixel) on the sensor, the configuration of the colour filter array (CFA) overlaid on it, and metadata. The CFA is a colour pattern filter overlain on the sensor that limits the spectral components gathered by each photo-diode to (usually) red, green or blue; the most common is known as a Bayer array and favours the green channel over the red and blue channels because this arrangement corresponds most closely to the colour perception of the human eye (Verhoeven 2010). Verhoeven (2010, 2016) provides useful and detailed discussions of this topic. The DNs form a grey-scale image, which must then be converted to a colour image by a process known as demosaicing, in which the intensity of colour in a particular channel can be determined for each pixel using the CFA data, and the other values (for those channels not represented at that particular point) are interpolated from those around it.

RAW files also preserve the whole dynamic range offered by the camera. The dynamic range can be characterised as the range of luminance that a camera can capture. In most cameras, the raw image is recorded using 12 or 14 bits (the bit depth) per channel. Twelve bits offer 4,096 shades per channel; 14 bits offer 16,384 shades per channel. When converted to JPEG, which only offers 8 bits per channel (256 shades), it clearly cannot transmit all of the information available, so some clipping of the dynamic range is necessary. A tonal curve is applied that will typically clip highlights at the expense of retaining better detail in the darker areas of the image (Stylianidis and Remondino 2016). This reduced dynamic range can result in posterisation in the final images.

A further consideration with JPEG files is their instability during and after processing. Re-saving a JPEG introduces compression errors, and this is compounded every time the file is re-saved, resulting in gradual degradation of image quality (Hass 2007; Verhoeven 2010). Retaining the RAW files means that the original data can be returned to at any point and re-processed with no loss of quality. Furthermore, nearly all digital cameras use different quantisation tables when writing in-camera JPEG files, so there is no real equivalence between the same settings on different cameras. For example a Nikon 'fine' JPEG setting is not the same as a Canon or a Sony setting (Hass 2007). It is evident, when comparing in-camera JPEG files from different manufactures with the RAW equivalents, that some are much more aggressive than others, whatever the setting chosen.

Although RAW files from different manufacturers contain the same basic information they vary widely in format. This is sometimes seen as a drawback, but in practice many image-processing programs are capable of handling raw image data from a wide variety of cameras. However, it can be a disadvantage for archiving. While Historic England advocates the retention of RAW files, these are converted to uncompressed TIFF files for archival deposition, largely because the TIFF format is perceived to be archivally 'stable', is supported across most platforms (for example Windows, Macintosh and UNIX) and can, with careful processing, represent a minimal loss of information from the RAW camera output.

In summary, RAW files contain (and retain) more information and have better compression (file size) than TIFF files, and also avoid the compression artefacts often found in JPEG files. However, there are some practical caveats to consider when advocating the use of RAW photography. RAW files are usually considerably larger than in-camera generated JPEG images, and consequently take longer to write. In some circumstances, for example when using a high-resolution camera on a fixed-wing SUA, the required time interval for taking shots with sufficient overlap is shorter than the time needed by the camera to write each file between exposures. This has to be compensated for by using one or more of the following:

- increasing the flight height to ensure overlap with fewer images, although this will have a detrimental effect on GSD and may, subject to Civil Aviation Authority (CAA) regulations in the UK, not be possible
- flying the area more than once to obtain complete coverage with a sufficient interval between exposures to ensure that the files can be written
- decreasing the focal length of the lens used to increase the coverage with each image
- changing the format from RAW to in-camera JPEG.

As the flying time required for an SUA is not usually very long at most archaeological sites, the second option is preferable because it has no effect on the GSD, does not adversely affect image quality and involves little inconvenience despite the extra flight time. There is usually no negative impact if a rotary SUA is used because the flying speed can be slow enough for the camera to write the files.

If you are using a camera that will only output images in JPEG format, it is advisable to use settings that yield the largest file size and the lowest compression ratio at capture, and to convert the files to TIFF immediately after download. There is little utility in using in-camera generated TIFF files if this is an option, because that results in the loss of the original RAW information and much larger files. In an ideal situation, both RAW and JPEG files should be recorded; this allows rapid assessment of the suitability of the images on-site, and the identification of any omissions or potential problems, before processing the RAW files when back in the office. Despite all of the above, however, it should be noted that much of the more popular software used for SfM–MVS processing is able to cope with JPEG files and is often optimised to some degree for them, given the common requirement for their use by fixed-wing SUA.

2.1.9 Multispectral Imagery

Images derived from sensors operating outside that part of the electro-magnetic (EM) spectrum (Figure 30) that is visible to the human eye can be processed using a normal SfM–MVS photogrammetric workflow and have a wide range of well-documented archaeological applications. They can be used in conjunction with products derived from 'normal' red, green, blue channel (RGB) imagery in a number of useful ways, for example comparing and analysing near infra-red (NIR)-derived ortho-images with their RGB counterparts and by combining the channels from both sets of imagery to generate different outputs.

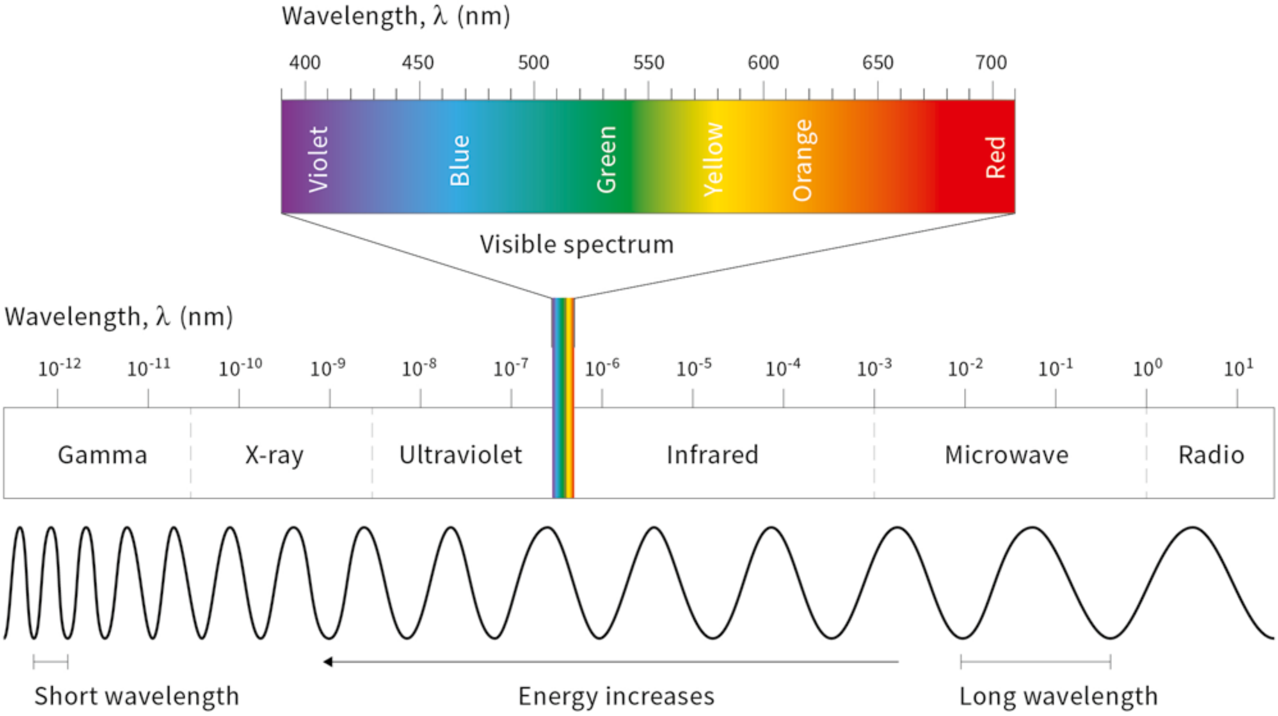


Figure 30
The electromagnetic spectrum.

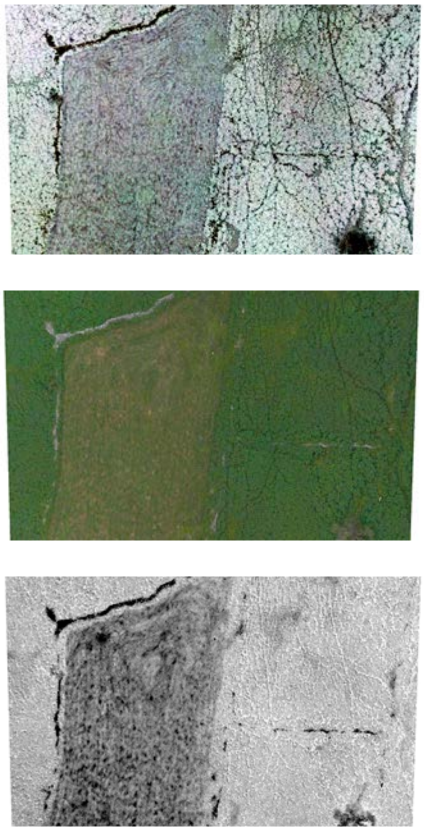


Figure 31
Unprocessed NIR (top) and RGB imagery (middle), with derived NDVI image (bottom).

NIR aerial photography has been usefully and comprehensively discussed by Verhoeven (2007, 2008, 2012) and has been evaluated on many sites in the UK (Dawson and Winterbottom 2003; Powlesland *et al* 1997). NIR photography's popularity derives in part from the relative cheapness and ease with which the necessary equipment can be obtained, as it often involves modification of an existing camera rather than the purchase of dedicated equipment. NIR imagery can be used on its own (usually after histogram stretching and contrast enhancement) or combined in various ways with the red, green or blue channels from visible spectrum imagery for estimating, for example, the normalised difference vegetation index (NDVI; originally developed for use with Landsat imagery in the 1970s) or fraction of absorbed photosynthetically active radiation (FAPAR), both measures of vegetation health (there are many others). Examples of such imagery are shown in Figure 31. In simple terms, diseased or stressed vegetation reflects less light in the NIR spectrum than healthy vegetation, and thus appears darker in NIR imagery.

Crop marks typically occur because sub-surface features either aid or hinder crop growth by increasing or reducing moisture availability and root penetration (Figure 32). They tend to be more apparent when crops are under stress from lack of moisture, which emphasises the differences in water availability throughout a crop. Buried ditches and trenches tend to retain moisture and allow deeper root penetration, leading to better crop growth, while walls tend to retain less water, leading to shallower root penetration, in turn leading to more stressed crops. In the visible part of the EM spectrum, the differences observed vary depending on vegetation type, and are principally showing the relative concentrations of different plant pigments (Tucker and Garrett 1977). Images taken with NIR cameras detect different variations, typically the number and arrangement of air spaces in the leaf structure and moisture content. RGB images therefore only show differences that are perceptible in the visible spectrum, whereas NIR imagery, which provides a better reflection of vegetation health, can show features that would be otherwise undetectable.

Although unmodified cameras with NIR filters applied to the lens can be used for terrestrial NIR photography, the long exposure times required to achieve good results preclude their use in aerial photography. For aerial NIR photography, DSLRs that have been modified by removing the hot mirror and replacing it with an NIR pass filter typically capture infra-red radiation in the 0.7µm to 1.4µm range (the visible part of the EM spectrum is between *circa* 0.38µm and 0.7µm). NIR images are also useful because the longer wavelengths in this part of the spectrum are less subject to atmospheric scattering, thus significantly reducing the effects of haze in high-altitude or oblique aerial photography (Verhoeven 2012).

Further up the EM spectrum, thermal imagery can also be used in conjunction with RGB photography to provide additional information, and has proved useful for detecting features in areas where dense vegetation precludes the use of RGB photography (Brumana *et al* 2013). Thermal imaging sensors are usually very low resolution compared with those in most RGB or modified NIR cameras (typically 640×480 or 320×240 pixels, depending on price), and therefore the images are processed separately and formal ground control is usually required to register it with imagery derived from other sources. Some photogrammetric packages may not be able to process imagery successfully at this low resolution.

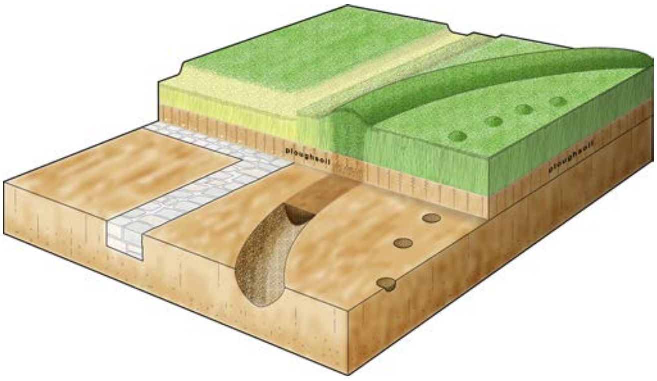


Figure 32
Sub-surface features and their effect on overlying crops.

2.1.10 Image enhancement

In general, image enhancement should be avoided and any functions that change the relative values of the pixel structures in an inconsistent manner should not be used when pre-processing images for photogrammetric purposes. Often, those methods that produce more visually pleasing images, by increasing apparent clarity for example, in fact adversely affect the image at the pixel level and can introduce artefacts.

Adjustment of the brightness/contrast (performed during the conversion of an image from raw to 8-bit) is sometimes useful, as is a minimal use of unsharp masking. Neither of these techniques should cause information loss or the introduction of artefacts (Chandler 2010) but do require prudent use and the results should be checked. Histogram equalisation, which can be used for manual photogrammetric digitisation, should generally not be used for processes that involve automated image matching: the software can distinguish slight variations in pixel values without having to apply the exaggeration necessary to make them visible to the human eye (Chandler 2010).

2.2 Image arrangement

Image arrangement for all photogrammetric work is underpinned by the fact that each point to be measured/recorded should be intersected by at least two rays (see section 1.2 The chief ray and principles of intersection), although in practice intersections from many more images are desirable. As the recent increase in the use of photogrammetric data in archaeology has focused (at least in part) on software that employs SfM techniques, image capture strategies for these are (briefly) discussed and illustrated in Image capture strategies.

2.2.1 Image capture strategies

2.2.1.1 Aerial

For aerial shoots, the types of images captured are to some extent determined by the platform employed. Fixed-wing SUA platforms will typically capture nadir (vertical), or near-nadir, imagery, whereas rotary platforms and manned aircraft open up the possibility of oblique image capture (Figure 33).

Forward overlaps for vertical imagery usually need to be at least 60 per cent, with lateral overlap between flight lines (or side lap) between 15 per cent and 40 per cent or higher (often 40–60 per cent in SUA imagery), depending on flight height (Figure 34). The Royal Institution of Chartered Surveyors (RICS) (2010) provides useful information on this topic.

A typical image arrangement from a fixed-wing SUA on a pre-planned flight path is shown in Figure 35. All the imagery is vertical or near-vertical. Vertical surfaces, such as cliffs or the sides of buildings, are generally not well represented, and, if these are required, additional oblique photography will be necessary. The degree of overlap achieved by these images is shown in Figure 36.

A typical arrangement of images of an archaeological site taken from a manned aircraft is shown in Figure 37. All the imagery is oblique. In this configuration, the overlap between images is very high and approaches 100 per cent,

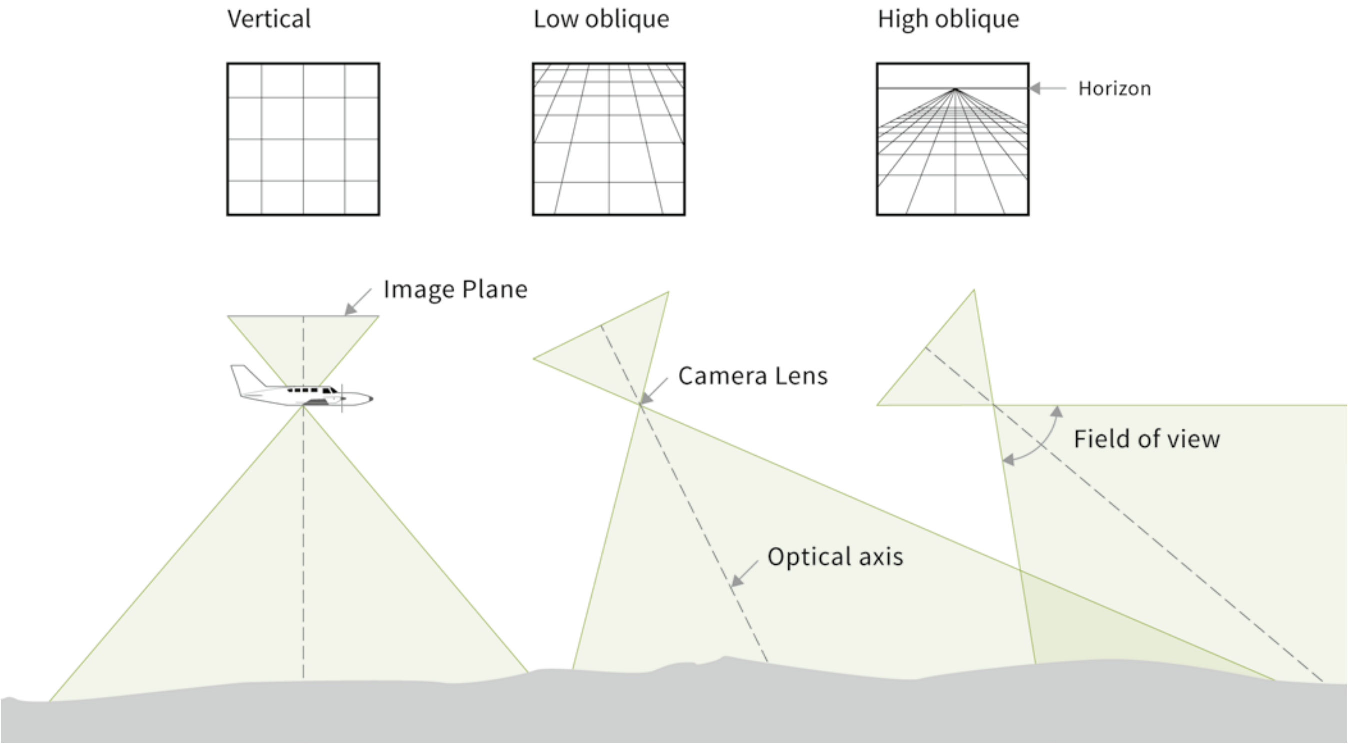


Figure 33
Different classes of aerial image.

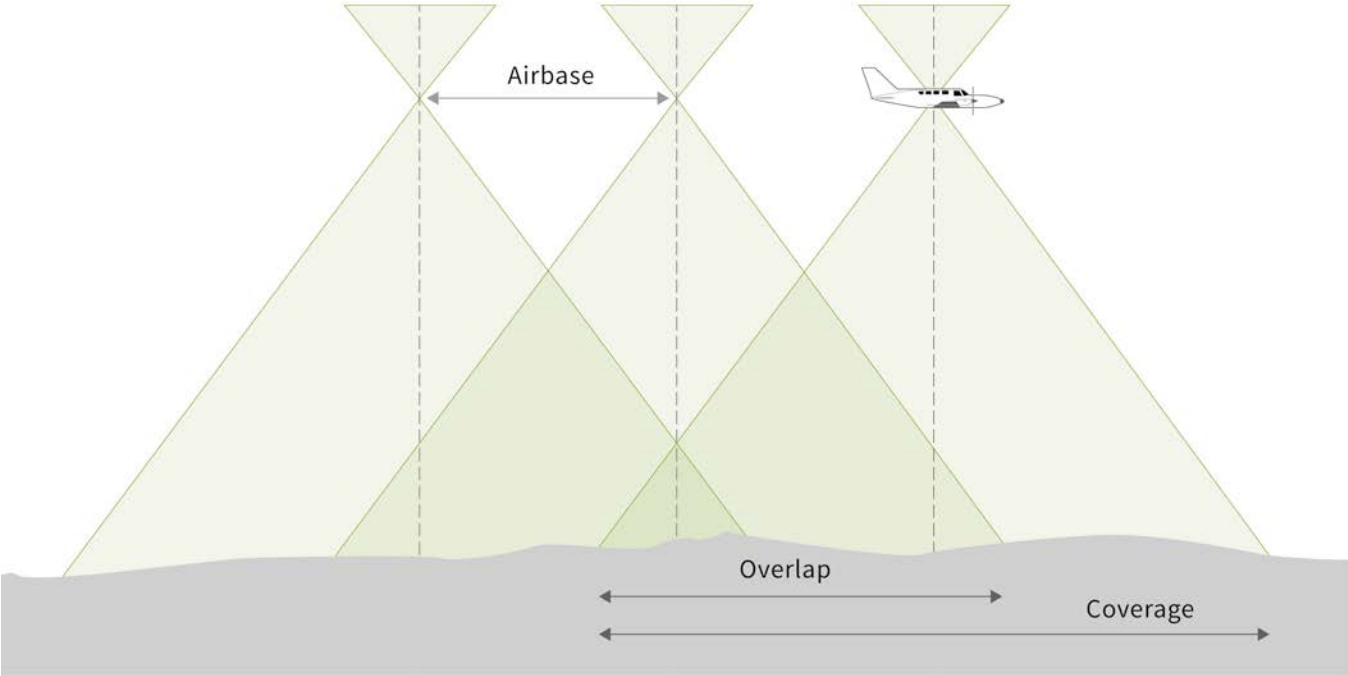


Figure 34
Forward overlap in vertical aerial imagery.

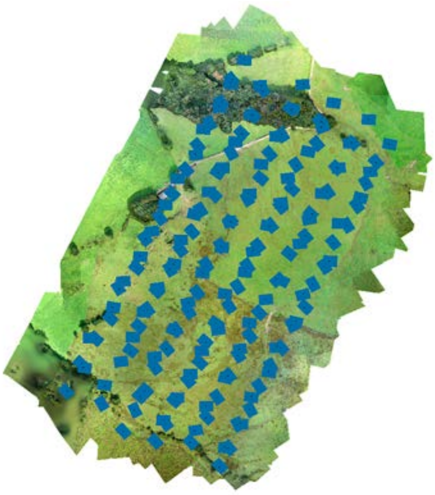


Figure 35
Typical arrangement of vertical images from a fixed-wing SUA.

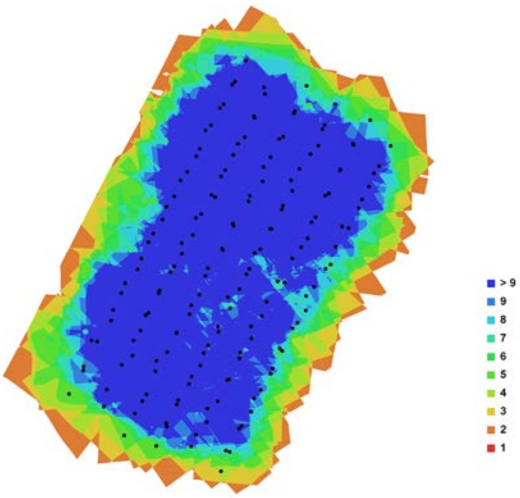
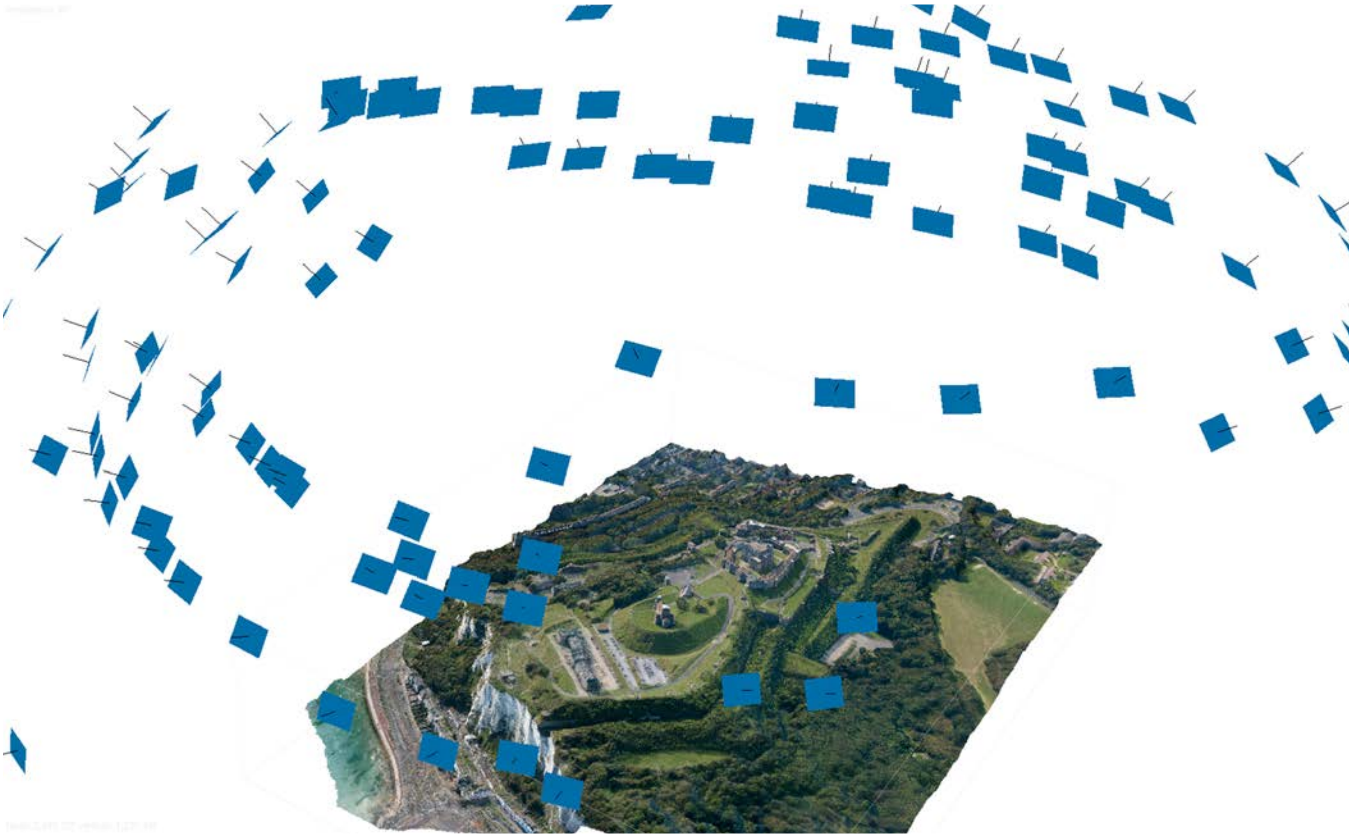


Figure 36
The overlap achieved by the imagery.



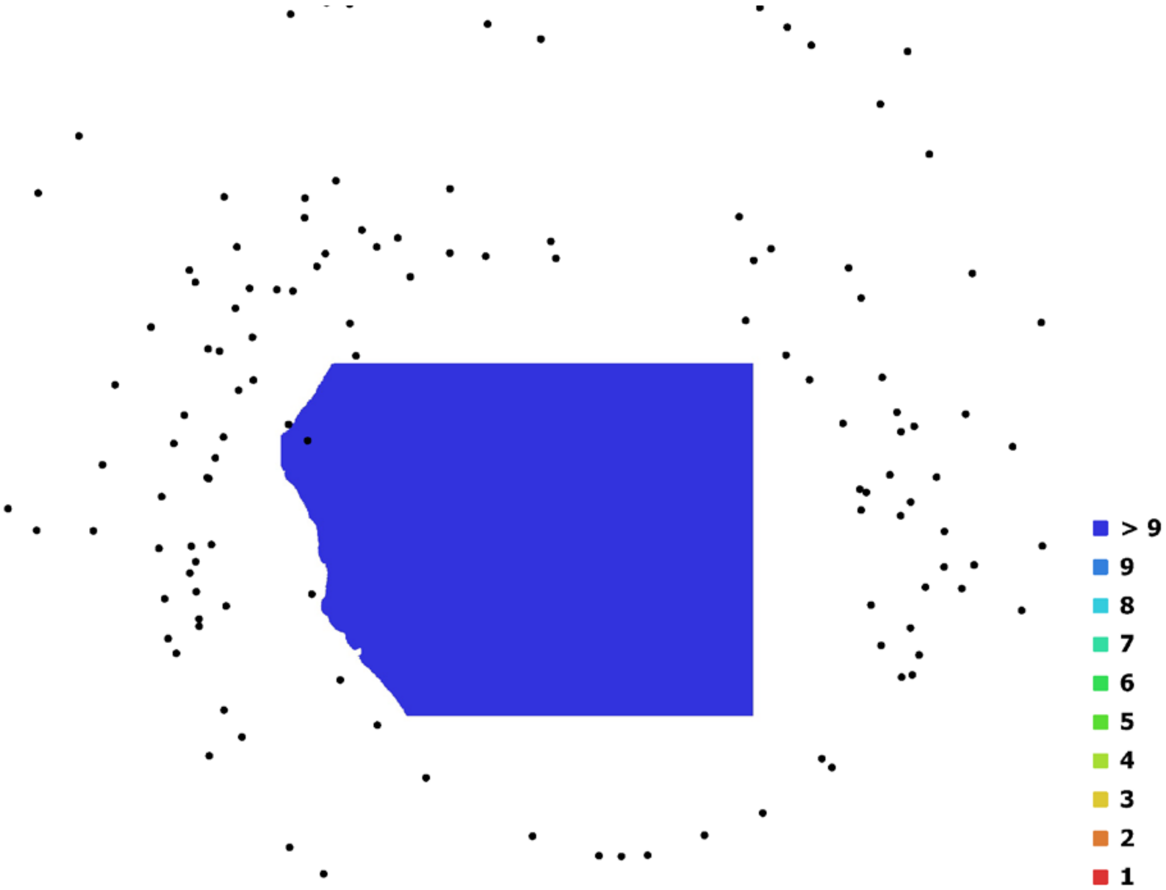
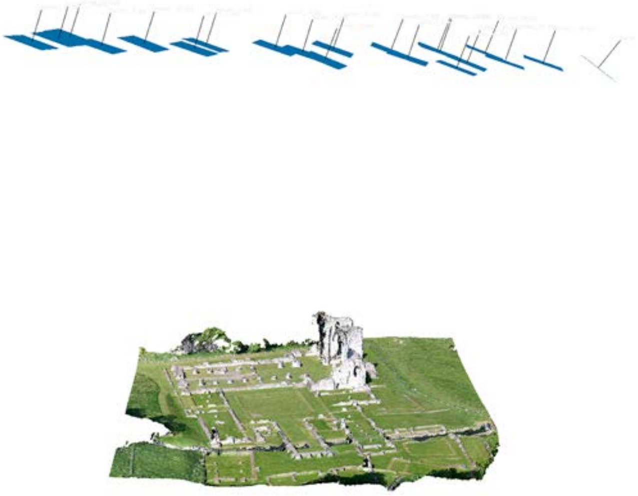
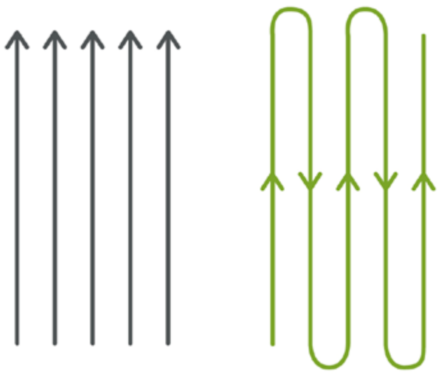


Figure 37 (top)
Typical arrangement of images of an archaeological site taken from a manned aircraft.

Figure 38 (above)
The overlap achieved by the imagery.





depending on the intervals between shots. Vertical surfaces, such as the sides of buildings, are well represented. The degree of overlap achieved by these images is shown in Figure 38.

Figures 39–41 show the processing of SUA imagery taken at Roche Abbey, South Yorkshire. The processing revealed that the camera had not been pointed directly downwards but at an angle in every shot (Figure 39). Had the images been taken with the camera angled and moving in a sequential pattern (Figure 40), the gaps would not have been significant. However, as all the images

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Figure 39 (top left)
Imagery that was supposed to be vertical taken at Roche Abbey, South Yorkshire.

Figure 40 (top right)
A different image capture strategy could have ameliorated the problem. The grey arrows indicate the actual flight lines; the green arrow shows a flight path giving better coverage.

Figure 41 (above)
As a result one side of the buildings is missing data.

were taken with the camera facing one way up the site, there was a considerable amount of missing data on one side of the building elevations (Figure 41).

2.2.1.2 Terrestrial

General image capture strategies commonly used for terrestrial shoots are shown in Figure 42. An image arrangement for the recording of a building elevation is shown in Figure 43. The lowest images were taken from a tripod on the ground; those from higher up were taken using a camera mounted on a 9m mast at two different heights. Although a plan view showing the roof only, the overlaps for the image arrangement shown in Figures 42 and 43 are illustrated in Figure 44 and are indicative of the overlaps seen on the building elevations.

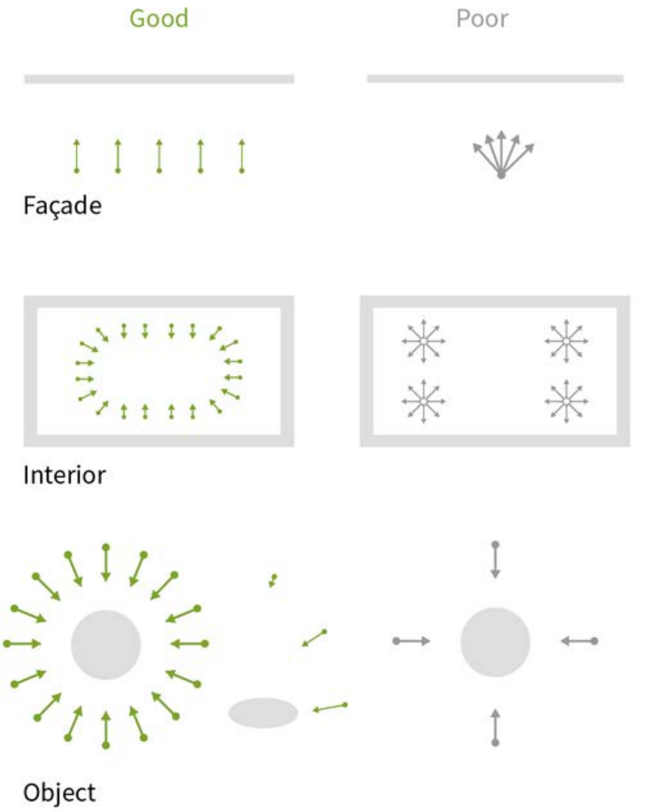


Figure 42 (above)
Image capture strategies for terrestrial photography. Adapted from Agisoft user manual (2017) Reproduced with permission.

Figure 43 (below left)
Typical arrangement of imagery taken for recording a building elevation.

Figure 44 (below right)
The overlap achieved by the imagery shown.

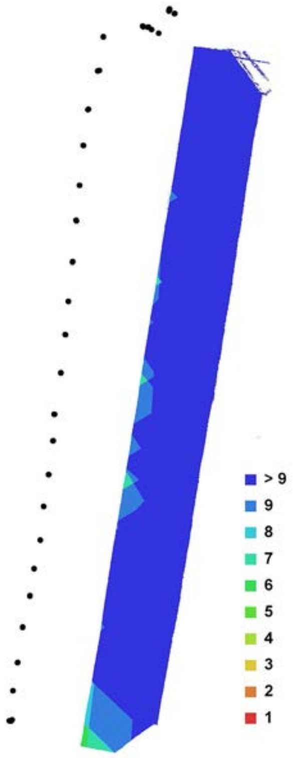


Figure 45
A building elevation photographed under very compromised circumstances.

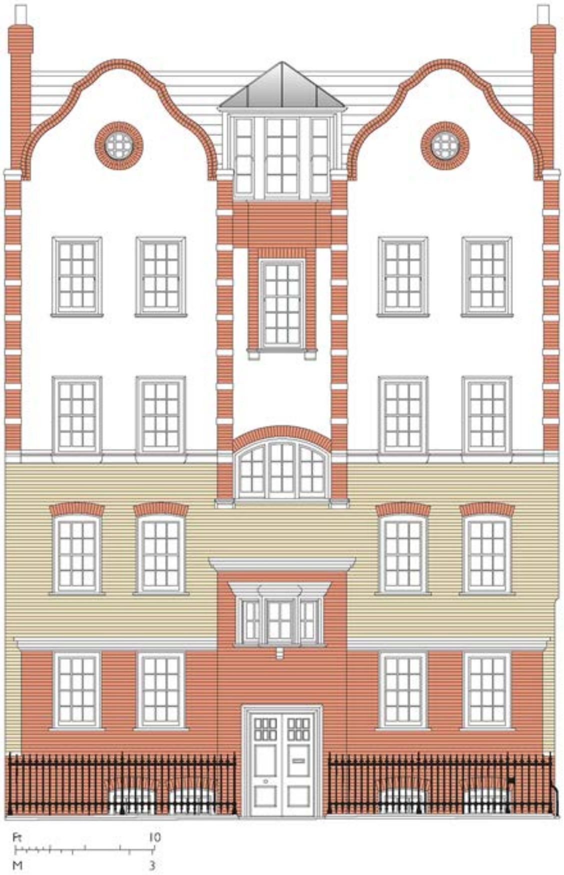


Figure 46
The illustration based on the imagery.

Another building elevation is shown in Figure 45. In this instance a mast could not be used to gain higher level imagery because of scaffolding, and the stand-off distance was compromised because the street was very narrow. This led to gaps in the data, notably on the upper edges of window sills and above most projections on the facade. As the required product was a line drawing produced in CAD rather than an ortho-image (Figure 46), these gaps could be tolerated and the additional information for roof lines and chimneys was infilled using a TST from some distance away and very obliquely.

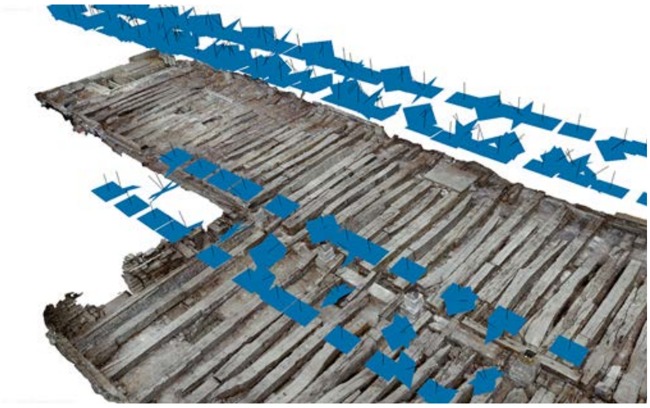
The image arrangement for a stone cross is shown in Figure 47. In order to capture the top of the subject, a camera mounted on a mast was used.

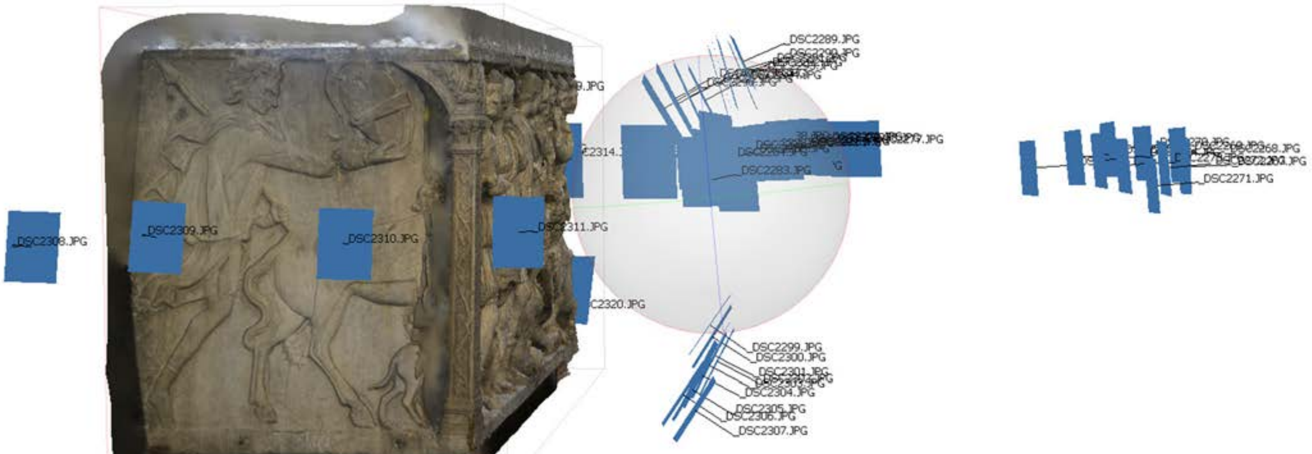
Figure 48 shows the modern re-processing of a series of images taken in a traditional stereo photogrammetric setup with an analogue camera in 1997 at Chatham dockyard, Kent. The images were taken to provide a series of stereo models that were then combined to form a single ortho-image. The SfM–MVS approach allowed the re-processing of the entire set of imagery at once.

For a piece of complex 3D geometry, such as the carved front of the sarcophagus shown in Figure 49, additional imagery has to be taken to infill possible gaps. As well as a series of images taken perpendicular to the face of the object, images were captured looking both down and up, both runs overlapping considerably (Figure 49).

Figure 47 (left)
Image arrangement used when recording a medieval stone cross.

Figure 48 (below)
Stereo cover arrangement with an analogue camera taken before SfM methods were available.





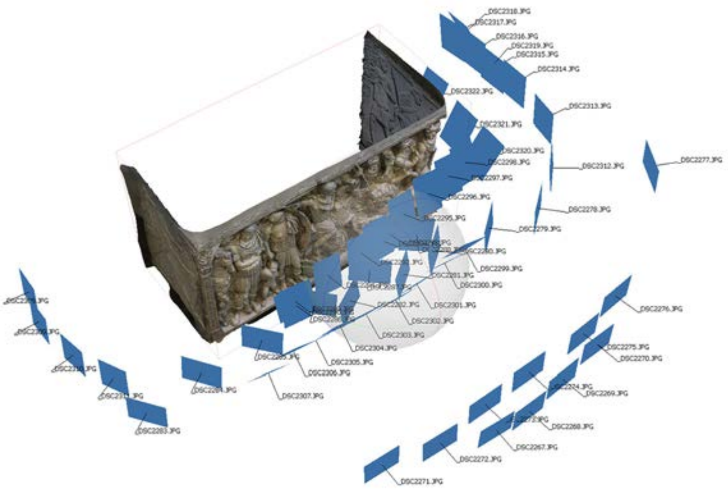


Figure 49
Image arrangement for a relatively geometrically complex carved object.

2.2.1.3 Small objects

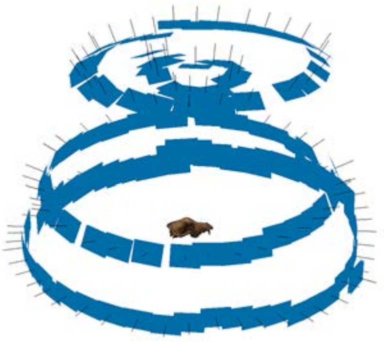
In this example, the partial skull of a small dog excavated from a Roman context at Raunds, Northamptonshire, was recorded. The skull, which was extremely delicate, was photographed using a static camera with the skull placed on a turntable, which was rotated slightly between each exposure. Images were taken at three height intervals as the object was rotated (Figure 50). The skull was then turned over and imaging repeated (Figure 51). The two models were aligned using common points from both models, giving the composite image arrangement shown in Figure 52. Each of the dense point clouds could then be cleaned up to remove extraneous points associated with the base on which they were placed and the callipers used as scale bars, and a single unified point cloud produced from which a mesh could be derived. With this type of project, achieving a high degree of overlap between the image sets of both sides of the object is very important, otherwise uniting the halves of the model successfully can be extremely difficult. This type of project is also easier if the subject has highly textured surfaces (with clearly definable common points) if control markers cannot be affixed to the object, as in the example illustrated.

2.2.2 The 3×3 rules

The original 3×3 rules, outlined here (Waldhäusl and Ogleby 1994), were published as a check list for the simple photogrammetric documentation of architecture. Although SfM photogrammetric techniques have rendered some of the original provisos redundant (such as keeping the inner orientation of the camera constant), they nonetheless remain a very useful set of reminders for a methodical approach that will yield great benefits.

The three geometric rules cover:

- control
- wide-area stereo image cover
- detailed stereo image cover



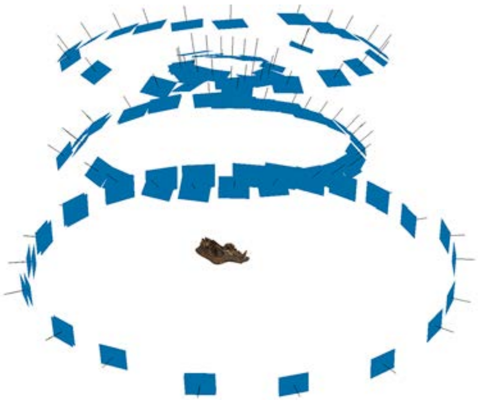


Figure 50 (top)
Images taken of the upper half of a small dog skull.

Figure 51 (middle)
Images taken of the lower half.

Figure 52 (bottom)
Composite image arrangement after alignment of the two halves.

The three camera rules cover:

- camera properties
- camera calibration
- image exposure

The three procedural rules cover:

- recording control and image layout
- metadata
- archive

The 3×3 rules have been updated to take account of more recent photogrammetric developments (TheoLt 2010).

2.3 Control

This section considers the use of externally measured control points for the purpose of model refinement, scaling, orientation and checking. Clearly, the SfM process itself involves the identification of large numbers of tie points between images, and these constitute an internal control network of sorts in their own right. If you are using a package without the facility to introduce external control measurements during the bundle adjustment, the tie points are the only correspondences that are used, without a measured 'real-world' spatial component. However, the main concern of this section is measured, coordinated points on or around the subject of interest.

Control for photogrammetry usually comprises a set of clear and unambiguous points that appear in the images and for which the coordinate positions are known. For aerial surveys, camera positions are also often recorded [using an on-board GNSS and inertial navigation system (INS), for example] and written to the image files as EXIF data; these can be used for approximate scaling and orientation of an otherwise unconstrained model if no ground control is available.

Control points can be in any reference system or coordinate frame, depending on the source data. The Ordnance Survey National Grid (OSNG) is often used in the UK for applications where spatial location relative to the national mapping framework is important. For other outputs, reference to a global coordinate frame, such as WGS84, may be preferable, whereas for building survey an arbitrary site coordinate system is often used. It is important that your software is able to handle projected coordinate systems correctly when you import control data.

Photogrammetric control performs the same function as control in many other forms of surveying: without it there is no check on internal errors, which may propagate throughout the model, and although things may 'look right' there is no guarantee that they are; a lack of control removes the facility to check for, quantify and mediate error. Control points are used not only to locate data spatially, but also to scale and orientate the data, for optimisation of the automatic image alignment and the reduction of non-linear errors in the model, and for checking the accuracy of the reconstruction.

Control may not be required in some situations, for example for work undertaken with only visualisation in mind or with low metric requirements. For accurate survey work, or where measurements may need to be taken from the model, control is essential, especially if the results are to be integrated with the products from other survey methods. Subjects that are 'full 3D' (for example a statue) will tend to perform better (as models with no control) than those that are 2.5D (for example most aerial subjects), as the imagery should 'close' all round the subject, reducing the chances of cumulative error propagation.

Ideally, control should be an integral part of a project from start to finish. Redundancy in your control network is useful: you should attempt to have more control points than you need, so that some of them can be used for optimising alignment, and scaling and orientating the project, and others can be used afterwards as check points to verify the accuracy of the reconstruction.

It is beyond the scope of this guidance to deal with the theory and practice of control network design. There are, however, a few basic considerations that can be applied successfully to almost any project.

2.3.1 General considerations

2.3.1.1 Number of control points

Photogrammetric models are, on their own, scale free. For scaling, a minimum of two control points is needed. These need not be 3D coordinates but may be points identified at the ends of a line of known length measured between two points visible in the images, for example a scale bar. This information can be used to scale, but not constrain the formation of, the model, which remains in an arbitrary coordinate frame.

For scaling and orientation, a minimum of three points is required, two of which must be 3D coordinates (that is *x*,*y*,*z* values) and one of which need only be 1D (*x*,*y* or *z*); they must all be visible in at least two images, but in practice should be visible in many more. Most software will in fact require three 3D coordinate values. With this number of control points, the model can be scaled, positioned and orientated relative to a coordinate frame, and thus achieve a degree of absolute accuracy, but the relative accuracy of the model will remain unaffected (the control points are used for scaling and orientation but do not contribute to adjustments in the formation of the model).

If you wish to use control points to refine the estimated image alignment and hence the accuracy of the reconstruction, you will need more than three 3D points. It is therefore advisable to use more than the minimum number of points, but the number of control points required varies to some extent with the complexity of the subject. For aerial surveys, for example, areas with relatively little topographic variation may require as few as 6–10 control points, whereas the accurate reconstruction of more topographically variable terrain will benefit from additional points (Figure 53). Similarly in building survey, fewer control points are required for accurate reconstructions of relatively flat facades than for more geometrically complex subjects. However, adding ever more control points to the adjustment yields diminishing returns in terms of increased accuracy. In all cases, additional measurements that can be used later as check points (not to refine the alignment but to verify the accuracy of the reconstruction) are advisable.

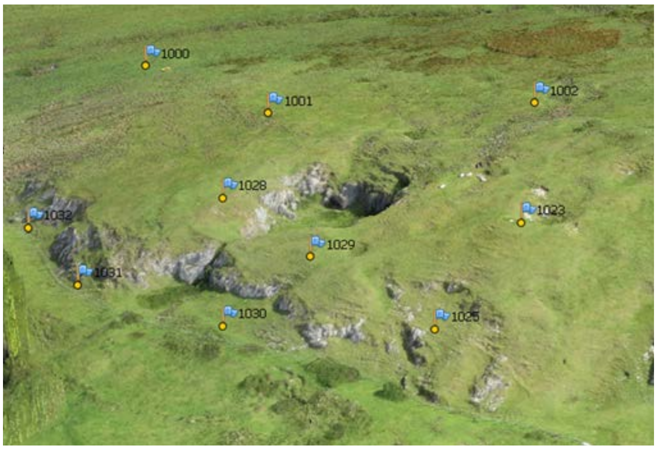


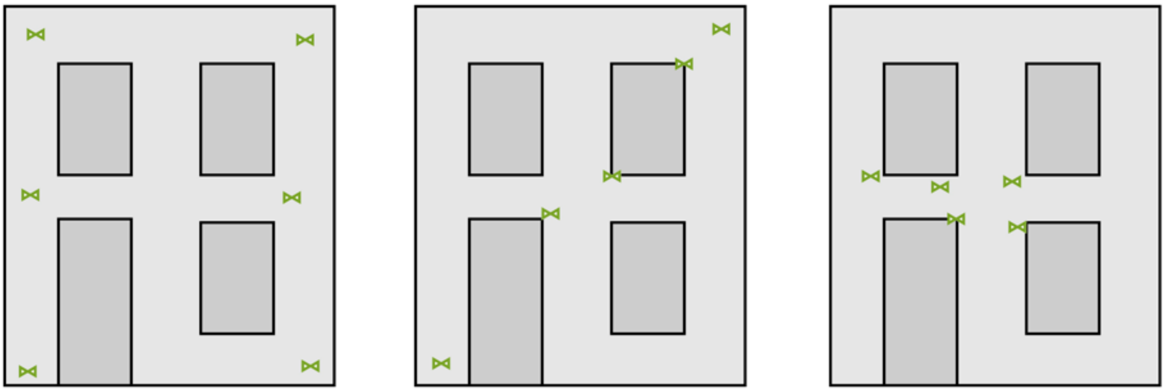
Figure 53
Additional control points are required in areas of topographically more variable terrain.

2.3.1.2 Distribution of control points

You should try to keep control points evenly distributed across the area of the model rather than grouped in a particular area or in a straight line (Figure 54). For aerial recording, place points near, rather than at, the edges of your area of interest, to ensure that the edges receive enough image coverage. If you do need to place the control points right at the edges of the study area, try to extend the flight area slightly to ensure sufficient coverage. One or more additional points placed centrally within the area is often sufficient if the topography is relatively even; if there is considerable variation, placing points near, for example, the tops and bases of significant topographic features is helpful. The same principle holds true for architectural and other recording: distribute controls as evenly as possible across the subject, and pay attention to significant projections or recessions. Most photogrammetric software that deals with external control has extensive documentation that discusses control points and their use, and it is well worth reading this before starting a project.

2.3.1.3 Accuracy and control points

It is useful to distinguish between relative accuracy (the accuracy of the photogrammetric reconstruction itself) and absolute accuracy (the accuracy with which the model is placed within a coordinate frame). The number of control points used can contribute to absolute accuracy only



good configuration
of control points

poor configuration
of control points

Figure 54
Control point distribution.

Control markers for aerial survey

In order to mark ground control points (GCPs) accurately in images, they must be of sufficient size to be clearly visible. Thus for aerial photography, the target size should be approximately 5–10 times the ground sample distance (GSD) of the survey, both to enable it to be clearly visible and for the point to be marked accurately; for example, for an aerial survey with a GSD of 40mm, targets between 20 and 400mm across (or larger) should be used. There are many choices regarding the type of marker used in the field, but they must be of sufficient size for the measured centres to be clearly visible in the images. In some cases well-defined ground features (for example centres of manhole/drain covers) can be used, but temporary targets, such as spray-painted crosses using dispersible, non-toxic paint, may be necessary, especially in areas where hard detail is lacking. A wide variety of aerial photography targets is available from most survey suppliers, and some examples are shown in Figure 55. It is not advisable to use building corners or points very close to tree cover, because global navigation satellite systems (GNSS) accuracy is often compromised in such areas.

Figure 55
Sample aerial photography targets.

(placing an otherwise unconstrained model in a coordinate frame) or to both absolute and relative accuracy (constraining and refining model creation as well as scaling and orientating it). The accuracy of GCPs is mainly dependent on (a) the positional accuracy of the method used to derive them and (b) the accuracy of their identification and placement in the images. If only camera location data is used, no image placement is necessary as the recorded camera positions themselves provide the control. Control should be measured with a degree of accuracy appropriate for the general requirements of the project, and need not be of a higher accuracy than is necessary. Survey-grade GNSS coordinates with a positional accuracy of 1–30mm will not usually be economic for a project where metre or broader accuracy is all that is needed, and alternative control sources can be more appropriate.

The accuracy of an entire project is subject to a large number of variables and should match the initial specifications for the accuracy required. These variables include, but are not limited to:

- image configuration (for example flight plan/completeness of coverage, flight height/stand-off)
- sensor quality/resolution
- image quality
- ambient conditions (for example weather, lighting)
- accuracy of control method chosen (for example GNSS, TST, scale bars) and marking on images
- distribution and number of control points
- the relative skill of the surveyor
- the processing techniques to be used and software options chosen.

Because of these factors, check points are the best method for assessing the metric quality of the outputs. The relative accuracy for SUA surveys after processing is approximately 1–2 pixels in plan and 2–3 pixels in height (TSA 2013). If you use survey-grade GNSS to locate a suitable number of GCPs across the survey area, the GSD can be used to estimate the accuracy of the survey, thus with a GSD of 30mm the accuracy can be estimated at 3–60mm in plan and 60–90mm in height (TSA 2013).

2.3.2 Sources of control data

Control data can be derived from a number of sources. The method chosen will be dictated by the accuracy requirements of the project.

2.3.2.1 GNSS (aircraft/SUA on-board)

The typical accuracy of the on-camera GNSS units used by Historic England (the Nikon GP-1, with a manufacturer's quoted accuracy of 10m RMSE horizontally) is commensurate with the accuracy of most navigation-grade GNSS equipment. The typical accuracy of in-aircraft GNSS units for light aircraft (for example the Garmin GPS map 496) is 15m RMSE 95 per cent, down to <3m with differential global positioning system (DGPS) corrections (Garmin 2007). Most SUA have GNSS receivers with a similar performance, although some are available that use a DGPS solution to improve locational accuracy significantly. GNSS values are recorded at the point of image capture and embedded in the EXIF data of the images. Developments to increase accuracy in archaeological prospection include combining a GNSS receiver and an INS for estimating exterior orientation at the point of image capture from manned aircraft, to give an image position to approximately 2.5m and orientation to approximately 2° (Verhoeven *et al* 2013).

Such data can be used by most photogrammetric software for initial relative estimations of image position and, in cases where high accuracy is not a priority, can provide all the locational and control information necessary for a project. In most other aerial work the data will be used for the initial orientation only, and will be replaced as control points by higher accuracy ground-based

GSD and mapping scale

The ground sample distance (GSD) is the distance on the ground that is represented by the distance between adjacent pixel centres in an image (so in an image with a GSD of 50mm, each pixel will represent 50mm×50mm = 250mm^2), and, in digital cameras, is a function of the pixel dimensions of the sensor array, the focal length of the camera and the flying height (Neumann 2009). It represents the spatial resolution of an image, so it is only applicable (across a single image) to imagery taken perpendicular to the subject, such as vertical aerial imagery, or in an ortho-image. In oblique photographs it will vary across the image as the distance to the subject also varies (with pixels closer to the camera having a smaller GSD than those further away). It will also vary in vertical aerial photographs according to variations in terrain (higher points on the ground, such as the tops of hills, will be closer to the camera than lower points, such as the bases of valleys).

GSD may also be calculated for an output ortho-image generated from a number of oblique inputs, and most photogrammetric software will give an indication of the GSD of the product and allow it to be changed. It is a useful way of indicating the level of detail that can be reasonably expected from the inputs, based on their resolution.

A useful tool for calculating GSD if the other factors are known can be accessed via the Pix4D website.

Reducing the GSD, assuming the same camera system is used, requires more flight lines (because of lower flying altitude) and will produce more images, and hence require a longer processing time. It is recommended that, if procuring aerial photography from a third-party contractor, the GSD requirement should indicate a target GSD and a maximum permitted GSD in order to take account of terrain variation. Features that are smaller than the GSD will not normally be discernible on the imagery, although sub-pixel interpolation is possible with multiple images.

In general, a GSD of 40mm (equivalent to an image scale of 1:3 000, although dependant on the resolution of the image) is commensurate with a mapping scale of approximately 1:500 (with a horizontal RMSE of ±0.1m and a vertical RMSE of ±0.05m; RICS 2010). The Royal Institution of Chartered Surveyors (RICS) lists commonly used topographic mapping scales and their GSD requirements (RICS 2010), and The Survey Association (TSA) has some useful guidance notes covering this topic (TSA 2013, 2015).

coordinates. When using locational EXIF tags, which are usually written to image files in the WGS84 coordinate frame, it is worth remembering that the height reported is the height above the ellipsoid rather than the altitude of the aircraft relative to the ground.

2.3.2.2 GNSS (terrestrial)

Survey-grade GNSS is a common method of locating GCPs for aerial survey work, whether from manned aircraft or SUA. The accuracy of ground-based GNSS coordinates using survey-grade equipment varies according to a number of factors but should broadly be within 10–40mm under normal conditions (*Where on Earth Are We?*; accuracies for other grades of survey equipment are also given). This level of accuracy is clearly commensurate with the resolution of imagery acquired by SUA and the accuracy of the anticipated outputs. It is worth keeping an eye on the reported accuracy of your GCPs, as it will vary with time and location.

In many cases the GCP coordinate positions derived from ground-based GNSS measurement will be relative to a national coordinate frame (for example the British national grid) rather than the WGS84 coordinates derived from the image EXIF tags. If this is the case, whatever software is being used, remember to assign the appropriate coordinate system, so that the later products can be located correctly relative to data derived from other sources. Assigning incorrect projections by mistake may not be apparent immediately but can lead to significant errors in placement.

2.3.2.3 TST

A TST is often used for control work in building survey or archaeological excavation. It will typically provide points that are accurate to around 2mm +/- 2 parts per million (ppm) reflectorless at a distance of around 50m or less, which is the usual range for these applications. If your stand-off is much greater you will not be able to see the centre of a small target properly, and you need to remember that the laser dot size of the TST is variable with range because of beam spreading (for example, for a Leica TS15i it is *circa* 7×10mm at 30m and 8×20mm at 50m). Targets can range from small but unambiguous points of detail (for example the screws on a light fitting, ventilation covers, and corners of windows in building survey) to small adhesive stickers and traditional photogrammetric butterfly targets (Figure 56). If the subject is being laser scanned simultaneously, scanner targets can be incorporated into the control network, although the scanner data itself will provide sufficient control on its own in most circumstances,

Figure 56
Sample targets for terrestrial survey work.

especially if combined with imaging (see Laser scanners/lidar). Spherical scanner targets are clearly not usable in this way.

If you are using points of detail, which is the least intrusive method and can be the only option available if targets cannot be placed on surfaces, it is vital you keep good site notes showing the points so that they can be identified easily and accurately after fieldwork is complete. It is surprising how quickly information can be forgotten, and surveys potentially compromised, without good notes. Using an imaging TST, if available, is extremely helpful in this regard, as images of control points can be taken with the TST as they are measured and referenced to the defined control points (Figure 57). This can ameliorate any ambiguity arising from inadequate site notes, but bear in mind that photographs taken with survey instruments often perform poorly if they are pointing towards a light source or in low light conditions (Figure 58), so additional narrative photography and notes should be taken. As with aerial control, you need to be able to identify the target unambiguously in the images, and to be able to define the measured centre.

Figure 57 (top)
Use of an imaging TST to aid site notes.

Figure 58 (above)
Example of a poor image from an imaging TST in challenging lighting conditions.

2.3.2.4 Laser scanners/lidar

Data from laser scanners can provide excellent control for terrestrial photogrammetric projects. If the density of the scan data is sufficient, coordinates can be derived directly from the point cloud and these values input for the corresponding positions on the images. Scanner targets (often used for registering point clouds from different setups), if present in the imagery, can also be used: these are often detected automatically by the scanner and scanned at a higher resolution, helping ensure sufficient data density in these areas.

If data from photogrammetry is to be integrated successfully with scanner data to form a composite product, or the scanner data is to be used as a model for texturing with the photogrammetric images, then the scanner data has to be used as the control basis in order to provide sufficiently accurate matching. Alternative methods, such as using target values measured independently by a TST, do not usually provide the best fit. Laser scanner data works well as the control for a range of size of subjects, from building surveys to smaller objects. However, it is far easier to determine the position of a control point from laser scan data if the scanner is recording images as well as range data (although in many scanners there is a time penalty for this); some software (such as RealityCapture, can combine photogrammetric and scanner data but the imaging has to be taken on the scanner for successful matching of the two data sets. Bentley’s ContextCapture is also useful in this regard, and does not require colourised scans for matching.

For aerial photogrammetry, lidar can be used to provide control data. At typical lidar resolutions [for example, the Environment Agency (EA) data varies between 0.5m and 2m for most of the UK], the accuracy will not be the same as that derived by survey-grade GNSS but will be significantly better than that from global positioning system (GPS) EXIF tags alone. Smaller, lightweight lidar units that can be carried on a SUA typically scan at much higher resolutions than those in manned aircraft (largely because of their closer proximity to their target) and have the potential to provide much more accurate control if a photogrammetric survey is also required (for example for a high-resolution ortho-image). However, there are relatively few such units flying commercially in the UK at the time of writing.

2.3.2.5 Scale bars

For smaller subjects, scale bars can be very useful where formal control is not possible, and are also useful as a checking mechanism even if a control network is available. They can be used for scaling but not orientation, although right-angled scales can be used to define the *x* and *y* axes of an arbitrary coordinate system. Alternatively, set squares that are graduated on both perpendicular axes (preferably in the same units) can also be used for the same purpose.

Some successful photogrammetric community projects, such as the Northumberland and Durham Rock Art Project (NADRAP), have used scale bar arrangements successfully (Figure 59). Scale bars are accessible if survey equipment cannot be afforded, are easy to set up, and provide sufficient accuracy if absolute orientation is not required. However, one potential issue with set squares and scale bars is that they can occupy valuable space on the image and hence reduce the overall resolution of the image set. It is often useful to take both overall shots including the scale bars and more detailed images focusing closer in without the scale bars showing or encroaching on the subject.

When imaging smaller objects, it can be useful to have a sheet of gridded matte drafting film or graph paper underneath the subject, provided it is

Figure 59
Example of scale bar placement as used on the NADRAP project.
England’s Rock Art (ERA)

Figure 60 (top)
Gridded matte drafting film to aid definition of scale and orientation.

Figure 61 (above)
Coded targets around the object.

kept flat. Points on the film or paper can then be used to provide scale and orientation (Figure 60).

2.3.2.6 Coded targets

Many photogrammetric software packages allow the use of coded targets to provide arbitrary control. Such targets can be recognised automatically by the software as control points to help align images. They can be printed out and re-used from project to project, and are extremely useful when reconstructing objects digitally. Examples of coded targets are shown in Figure 61. Such targets can also be used at fixed spaces to provide scale bars that can be placed around the subject (for example see Cultural Heritage Imaging).

Coded targets must be of an appropriate size relative to the subject so that they can be identified accurately by the software. Their application in aerial survey is, generally speaking, impractical because of the dimensions they would have to be produced at.

2.3.2.7 Other sources

For some projects, control values may have to be used from other sources. For aerial projects, it is relatively straightforward to obtain *x*, *y* coordinates from a variety of mapping sources, the accuracy of these depending on the scale of mapping used. It is not quite so easy to obtain *z* (height) values of suitable accuracy, and most photogrammetric software will require 3D coordinates for control values.

If you have access to national mapping agency data, such as Ordnance Survey in the UK, you can use features visible in aerial photographs that have level information available from Ordnance Survey maps, for example spot heights on roads or manhole covers. These will only be approximate because they do not often coincide with features visible on the roads themselves, so the accuracies are limited to between 0.5m and 3m. The distribution of such points around a project area may be suboptimal for control but may be sufficient for orientation and scaling if no other data is available.

There are products available in the UK that can be used if ground control is otherwise unavailable and the required accuracy is low, for example OS Terrain 5, which has a 5m grid of spot heights available as well as contours, although background mapping will be required.

As a last resort, if geolocation, however approximate, is required, there are many web map services available, including free services such as Bing maps and Google maps , from which very coarse coordinate values can be obtained. Coordinates derived in this way should only be used for approximate scaling and orientation, not image alignment optimisation. The resolution of the data is not consistent across the globe, but these services can be appropriate if the desired output is a low-accuracy .kml file for use in an environment like Google Earth.

2.4 Historical imagery

SfM techniques can be used with historic photographic data if a few basic conditions are met. The quality of the output will be dependent largely on the following factors:

- sufficient overlap/completeness of coverage
- sharpness and focus
- print distortion (if prints rather than negatives are used)
- images are not cropped

Research into the metric performance of historical stereo aerial photographs (Papworth 2015; see case study 1) has demonstrated their potential for assessing and quantifying change over time. Imagery taken with ‘traditional’ photogrammetric outputs in mind can also be used and re-processed, including military reconnaissance photography and national mapping agency data. One of the major advantages of stereo photogrammetric imagery has always been that it does not require immediate processing: once the images have been captured it is not always necessary to go the expense of processing them,

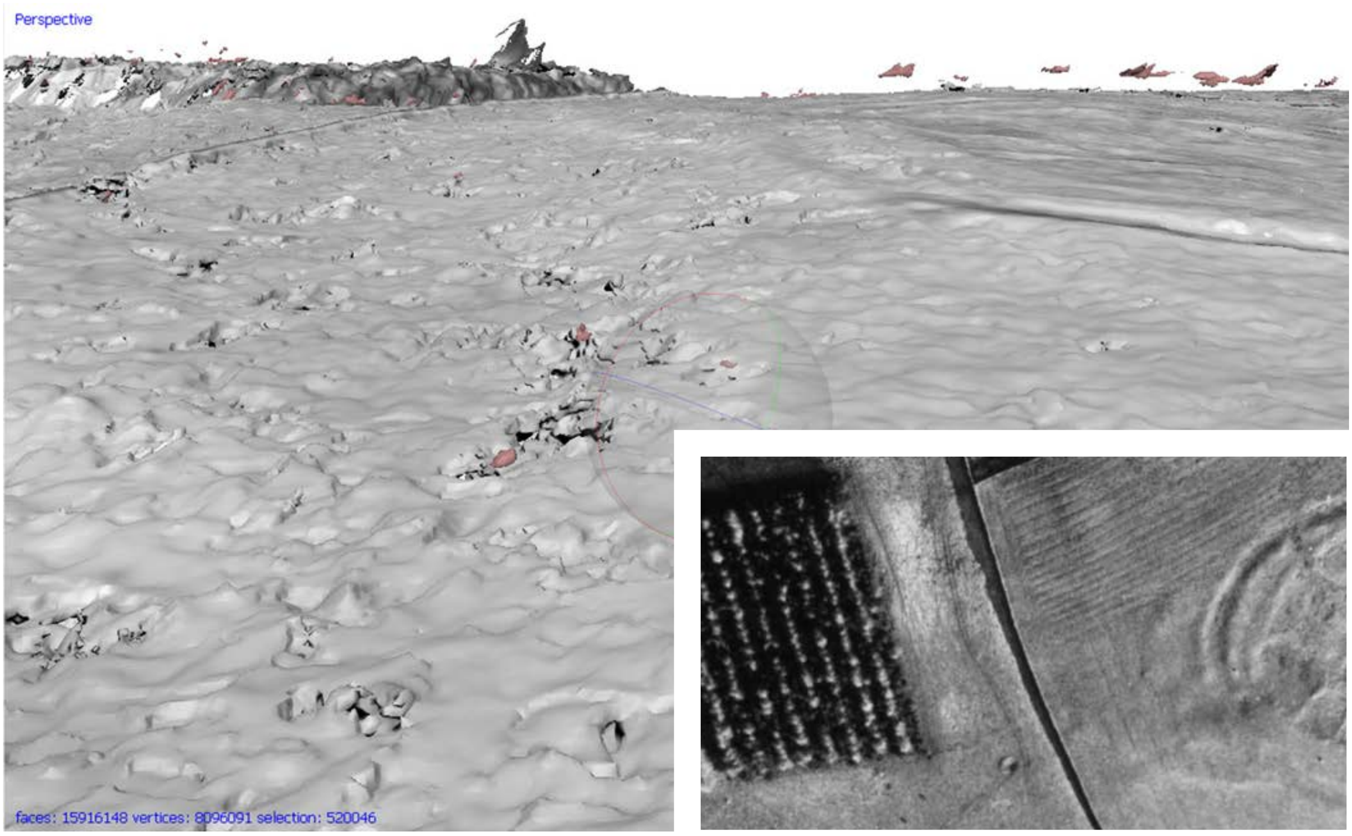


Figure 62
Historical imagery (inset) producing a poor model due to lack of clarity.

and they provide an ante-disaster record that can be used in the event of an emergency. Imagery acquired at Windsor Castle, Berkshire, before the fire of 1992, for example, was subsequently processed to inform the reconstruction and re-instatement of much of the damaged interiors.

With pre-digital imagery, it is often not possible to know with certainty which cameras or lenses were used, although this can be established more easily for aerial rather than terrestrial images. Most agencies collecting aerial data on a regular and systematic basis recorded metadata either in accompanying log books or around the edges of the image frames themselves; if these are available they should be used.

Figure 62 shows an example of a poor-quality model derived from oblique archive aerial imagery. It is acknowledged that this was never taken with photogrammetric processing in mind, but it provides a useful cautionary tale in the use of such imagery (Figure 62). One problem is that the images are not sharp and in focus; while they show the general form of the landscape under good lighting conditions, they are noisy. Furthermore, they were scanned from prints rather than negatives. The results show that although the general landform has been extracted, the noise in the inputs has led to noisy outputs, with the ground surface exhibiting a porridge-like texture, and a large amount of extraneous geometry being generated both above and below the general surface.

When scans of prints are used (see also desktop scanners (page 62)), it is essential for the photogrammetric process that the entire image frame is provided, otherwise the interior orientation of the camera cannot be estimated.

You should always be circumspect if given imagery that is tightly cropped with no visible indication of whether the image represents the entirety of the original or not. Similarly, it is not always immediately apparent whether a tilt/shift lens was used; if this is the case, results will be metrically poor because the estimations of interior orientation will be incorrect.

When comparing modern and historical data, there are several points to consider. It is usually best to compare imagery of similar scales, in order to avoid inconsistencies deriving primarily from variations in scale. For example, comparing historical Ordnance Survey vertical imagery taken at a flight height of approximately 10,000ft (3048m) with modern oblique imagery taken from a height of 1000ft (304.8m) can produce results that are potentially misleading. The GSD of the imagery taken from a higher altitude will often be considerably less than the GSD of the lower altitude imagery, and comparisons will therefore be compromised. Such comparisons are not wholly invalid, but you need to be aware of the inconsistencies in the inputs and take them into account when interpreting the results.

Consistency of control is another factor that has to be borne in mind, and is to some extent allied with issues of scale. The accuracy with which control points can be placed on small-scale images will be less than that in large-scale images. Additionally, and especially if there has been considerable variation of the ground surface over time, choosing consistent control points can present difficulties. As the control points will form the basis for the comparison between the data, they need to be as consistent as possible, and as many common points should be used as is practicable. Historical imagery can also be used for the reconstruction of lost sites, for example as a result of coastal erosion or wartime destruction.

3 Scales and Applications

One of the distinguishing features of a convergent multi-image SfM photogrammetric approach is its sheer versatility at a range of scales. The same cameras (and to some extent lenses) can be used for anything from landscape survey to small objects. The approaches at varying scales have many similarities, and the common factors are addressed in General considerations (section 2). This section addresses the special considerations needed at different scales, focusing on the platforms used to obtain the images and the characteristics of the subject matter.

3.1 Aerial photogrammetry for archaeology, landscapes and buildings

There are many potential applications for aerial photogrammetry in archaeology. It is a well-established discipline in other sectors, with many years of 'traditional' photogrammetric processing producing mapping for national mapping agencies, military and industrial applications and many others worldwide. Archaeological uses of aerial photogrammetry have, until recent years, been less prominent, largely because of the cost of image acquisition and the equipment and expertise required to process the photographs, although single-image rectification using height displacement correction has been a mainstay of the Historic England (English Heritage) national mapping programme for more than 20 years. The advent of affordable photogrammetric software coupled with more powerful computers and the availability of suitable SUA and good-quality digital cameras has seen an explosion in the use of low-level aerial photogrammetry across all geo-information sectors, archaeology not least among them.

Before discussing some of the more accessible ways of acquiring and using aerial photogrammetric data, some distinctions between it and other commonly used data sets need to be made. Lidar data is used extensively in aerial archaeology (*The Light Fantastic: Using Airborne lidar in Archaeological Survey*). While a lidar data set is often used as a raster image (in, for example, a GIS), this image will have been derived, in most cases, from full-waveform lidar scanner data, in which first and last returns can be discriminated along with many subdivisions between them. This allows, for example, the recovery of data representing the ground surface beneath a tree canopy in wooded areas by filtering the data and using last returns to form a digital terrain model (DTM). Photogrammetric data is, in these terms, first return only: if the camera cannot see a sufficient amount of the ground surface beneath a canopy, it cannot be modelled because there is no data (there are no pixels in the input images) representing it. Thus photogrammetry is not particularly useful in heavily wooded areas. As such, a DSM (as opposed to a DTM) is the usual product. With regard to this, in areas with few or relatively well spaced trees, oblique photography that shows the ground surface under the tree canopies can be extremely useful for filling in the gaps when combined with vertical images, and allows the safe removal of canopy-related points without detracting from the quality of the derived DTM.

Similarly, in areas under agricultural cultivation, the DSM derived by photogrammetry will represent the tops of the crops planted (first return) rather than the ground surface below (last return): as already mentioned, photogrammetry provides a first-return only output so, unless the crop is sufficiently sparse, the ground surface will remain invisible. This is not necessarily a major disadvantage, but it should certainly be borne in mind when processing the data, especially when incorporating ground control measurements that have been taken from the surface of the soil in which the crops are growing. Depending on the maturity of the crop, significant differences between the heights of the GCPs and the derived surface may become apparent. Some filtering of photogrammetric point clouds is possible, however, and removal of noise in the data set from sparse vegetation can be undertaken, as well as the removal of large areas of tree canopy and buildings (see case study 3). Care should be taken with other features likely to be visible in the images: static livestock and vehicles, for example, will require manual removal, and once removed any surface 'beneath' them will be interpolated from the surrounding surface if the holes are filled in (which will happen if, for example, a raster surface is exported to GIS).

Figure 63
Parts of the SUA airframe visible in the photography.
© Skyline Images

One of the significant advantages of photogrammetrically acquired data over lidar is resolution. Lidar is available for much of the UK at a nominal resolution of 2m (an average post spacing of one return every $2m^2$), with some areas covered at 1m, 0.5m and 0.25m resolutions. While this provides a considerable amount of information regarding larger features, such as those typically identified during aerial prospection, in many cases it does not allow the identification of smaller surface features. Photogrammetric data derived from an SUA or a manned aircraft will typically have a resolution between 0.02m and 0.1m, permitting the identification and analysis of much more subtle features, although usually, in the case of an SUA over smaller areas and discrete sites, the derived data sets can be huge and flying times are limited. A manned aircraft, in contrast, allows many sites (20+) to be covered during a single flight. Despite the differences in resolution, once the data has been derived the analytical stages are very similar to those employed when using a lidar DTM as the source.

With some aerial platforms you may get parts of the aircraft in the photographs, particularly if very large wide-angle lenses are used (Figure 63). If this is the case, you will have to mask-out the aircraft from the inputs, if possible, or re-fly the area. If part of the aircraft is in the same place in every photograph, some software packages have mechanisms to cope with this (normally used for masking fiducial marks and other data commonly placed around the edges of aerial images). If the location of the aircraft image varies, the images will normally require manual editing to mask the aircraft. Kite-derived photography will commonly have control lines and the operator visible in vertical or near-vertical shots, though these are not as problematic as parts of an aircraft or SUA.

In all cases, overlap is essential. Vertical aerial photography will typically have a front-to-back overlap of between 60 per cent and 80 per cent, with a side lap between swaths of 40–60 per cent (see section 2.2 Image arrangement). Oblique aerial archaeological photography, such as that typically taken from a light aircraft, should achieve considerable overlap between images when orbiting the subject, preferably without leaving gaps around one side of the subject (so as near a complete circle as possible). It is generally best to remove any high oblique ‘scene-setting’ shots when processing (Figure 64) as they will rarely align properly. The lighting requirements for images to be processed photogrammetrically are more forgiving than those usually used in archaeological aerial photography, which traditionally uses low-raking sun angles to emphasise the 3D nature of the features on the ground (see section 3.4.2 Lighting). For photogrammetric purposes, images taken on overcast days with even lighting across the scene are generally preferable; provided the images are of good enough quality, the software will be able to compute the 3D aspects of the site, which can then be emphasised by other means during later processing, for example by moving a ‘virtual sun’ around the surface in a GIS to emphasise or elucidate features. However, this does not preclude the use of more ‘traditional’ aerial photography for SfM: ortho-images generated from such inputs are visually pleasing and easier to interpret, especially to the untrained eye (Figure 65).

You need to place GCPs before undertaking photography of subjects with poor textural variation, for example an apparently featureless grassed field where no distinctive points can be discerned, or extend the target area to include details that will allow both matching and geolocation. On a windy day, when the grass or crop is likely to be moving and the surface will be slightly different in each shot, very low-level aerial photography will not yield results that are interpretable without ground control. This is rarely a problem when using photography from a manned aircraft (because the flight height almost always allows the capture of detail that can be used by the software to incorporate matching) or with an SUA, but it becomes more problematic the closer to the ground you are, when less of the subject is visible in each photograph. In these

Figure 64
High oblique imagery that is unlikely to process well.

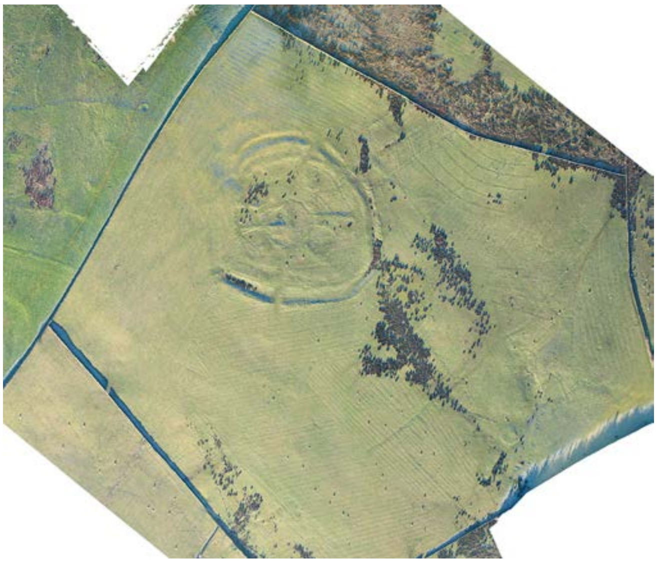


Figure 65
Aerial imagery taken with a low sun angle provides an easily interpretable ortho-image.

cases, the GCPs can be used to help correct the orientation of the images as long as sufficient numbers of them are visible; an alternative strategy is to increase the flight height to ensure that more of the surface is visible in each image.

Other problems that are encountered with aerial imagery typically include those that result from variations in ambient conditions during photography and those that result from variations in ground conditions. An example of changing ground conditions is shown in Figure 66. This site was photographed once in the morning, when some snow cover was present, and again later the same day, when the snow had melted. In such cases, matching between the different runs using all the inputs at once is likely to be poor, so they need to be processed separately and the dense point clouds merged later using GCPs. A subset of the images can be used for producing an ortho-image or texturing.

Figure 66
Changeable ground conditions during photography.

Significant changes in ambient light (for example bright sunlight at the beginning of a run or heavy cloud cover towards the end of a run) are often encountered in the UK, although this usually only affects longer capture periods. If only a surface model is required, and the differences in lighting are not too great, then variably lit image sets can be used. If an ortho-image is needed then it is worth waiting for relatively stable conditions to ensure that the result is consistent across the entire image, and to make it easier to carry out the image matching. Some software offers colour correction when generating textures or ortho-images from inputs with variable lighting, although this can significantly increase the time taken to generate the outputs. It is usually better to take the images under consistent lighting conditions in the first place, if conditions allow.

Figure 67
Haze in aerial imagery taken from a manned aircraft.

Haze in aerial photographs can be a problem, particularly with images taken from higher altitudes (from a manned aircraft), because it obscures ground detail and makes the matching of points on the ground surface more difficult. Variability in haze can also lead to inconsistency between shots, even in a single run. Photographs with significant interference from atmospheric haze will not process well and should be discarded if possible. If photogrammetry is an intended product, you should choose conditions when the air is relatively clear for photography, and avoid oblique shots as far as possible: haze becomes more of a problem the more oblique the shot because its effect on more distant subject matter is more pronounced (Figure 67).

GSD is explained in box 3. For the different scales of output often associated with topographic or archaeological landscape survey, the maximum GSDs accepted by Historic England when procuring survey from external contractors (Andrews *et al* 2015) are shown in Table 2.

Output scale	Maximum GSD
1:100	10mm
1:200	20mm
1:500	40mm

Table 2

Table 3 shows suitable GSDs (approximate values) suggested by the RICS (2010).

Output scale	Maximum GSD
1:1 250	75mm
1:2 500	150mm

Table 3

3.1.1 Platforms

3.1.1.1 Manned aircraft

The use of manned aircraft for archaeological aerial photography is well established, well understood and extensively covered in archaeological and scientific literature. It will not be dealt with in great detail here, other than to outline the photographic requirements for successful photogrammetric processing of the outputs. Two Cessna 172s are used by Historic England for manned aircraft image acquisition, using Nikon D3X and D810 DSLRs. Typical outputs are sets of vertical, near-vertical and oblique images for each site on the flight plan, the oblique images usually requiring circling or arcing around the site (Figure 68). Many sites are often included in a single flight, for reasons of economy, which means the images have to be separated into discrete sites before processing by most software. Although oblique and highly convergent image sets are a long way from those captured for traditional cartographic photogrammetry, they process very well in SfM–MVS-based packages because the overlap on the subject matter can be up to 100 per cent. A few input images, if of sufficiently high quality and with locational EXIF tags, can be processed extremely rapidly to produce ortho-images and other products if absolute accuracy of a high order is not required. If high-quality sensors are used, GSDs of 50mm are easily achievable. In this case, ground control obtained from lidar data can place the model to within 1 or 2m with very little additional effort (Figure 69).

There are significant advantages to using manned aircraft, with or without vertical imaging capability (from a port in the bottom of the aircraft through which to point the camera), including the number of sites that can be covered in a single flight, the wide areas over which data can be gathered and the weight and number of sensors that can be carried. The GSD achievable is comparable with that from a normal SUA at 100m and more than adequate for most archaeological survey purposes. With the right camera and lens combination, manned aircraft photography can also be extremely effective for aerial city modelling. The key disadvantage for smaller operations is a lack of pilots offering the service for imagery of single sites, in which case the cost benefits of SUA in comparison become apparent, but for Historic England the in-house capability provides good value for money given the large number of sites distributed over wide areas that it is required to cover.

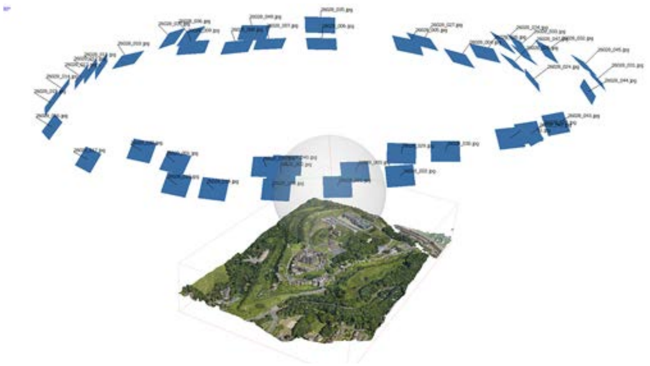


Figure 68
Aerial archaeological photography from a manned aircraft – circling configuration.

3.1.1.2 SUA

There is a plethora of terms for small aerial vehicles capable of carrying a sensor (in the photogrammetric case usually a camera). Remotely piloted aircraft systems (RPAS) is the term that is increasingly being used across Europe, although other popular terms include small unmanned aircraft (SUA, used here) and unmanned aerial vehicle (UAV), as well as the ubiquitous 'drone'.

SUA are defined by the CAA in the UK as 'any unmanned aircraft, other than a balloon or a kite, having a mass of not more than 20kg without its fuel but including any articles or equipment installed in or attached to the aircraft at the commencement of its flight', and by the International Civil Aviation Organisation (ICAO) as 'A set of configurable elements consisting of a remotely piloted aircraft, its associated remote pilot station(s), the required command and control links and any other system elements as may be required, at any point during flight operation' (ICAO Circular 328). SUA fall broadly into two categories: fixed-wing and rotary. Both have advantages and disadvantages.

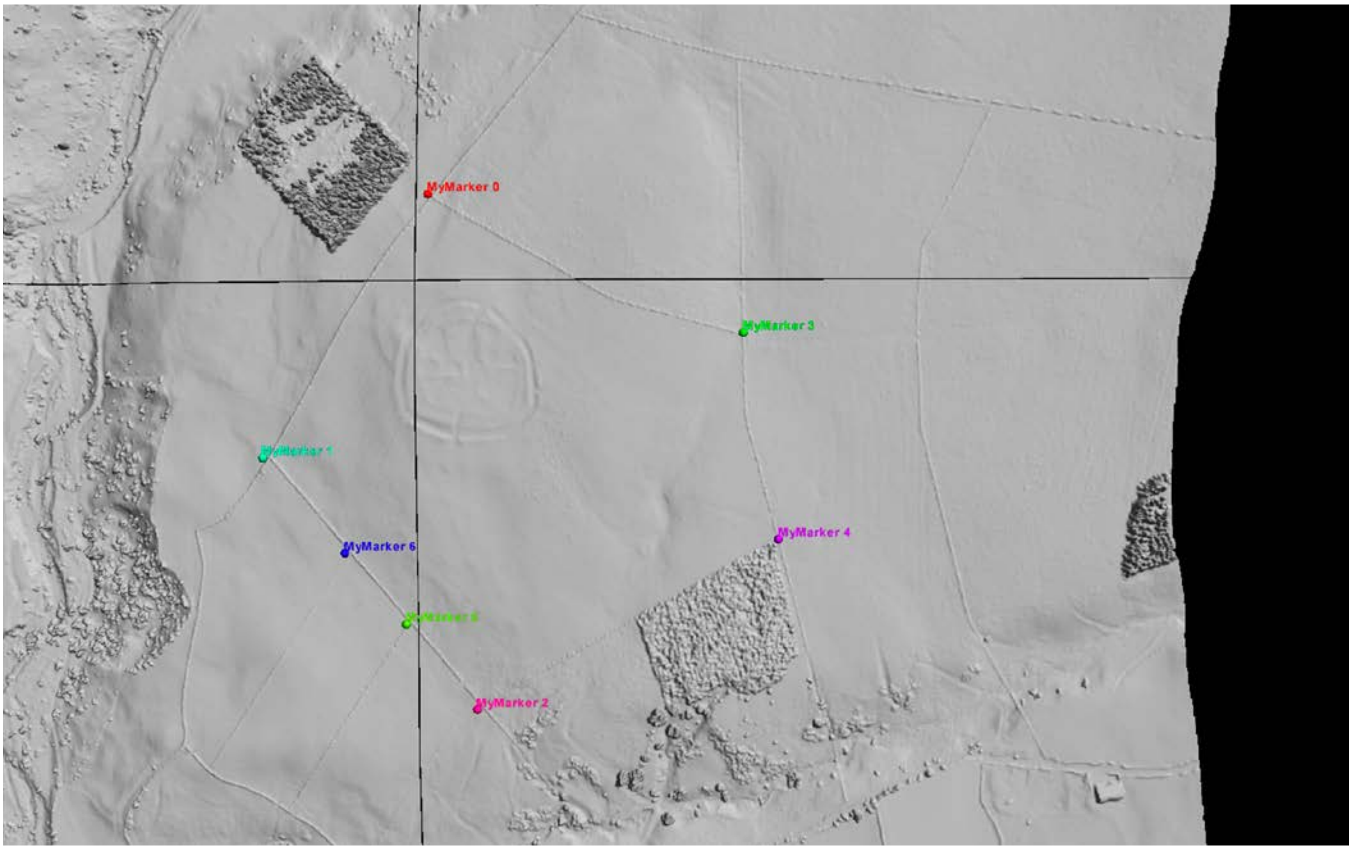


Figure 69
Coordinates from lidar used as ground control.

Fixed-wing SUA tend to give a more 'traditional' photogrammetric output, usually shooting overlapping swaths of vertical or near-vertical photography in the most efficient manner. They can typically cover quite large areas in a single flight (generally about 1km^2, which is the limit of legal 'line of sight' CAA regulations in the UK) and are thus effective for the surveying and mapping of landscapes and open sites. Flight durations are typically up to 45min on a single battery. With spare batteries, good weather and good planning, several flights can be undertaken in a day. For relatively straightforward mapping cases (open sites with earthworks, for example), vertical imagery on its own is perfectly adequate, but often a combination of vertical and oblique imagery is needed, not only for more complete representation of vertical elements but also because oblique images can be usefully employed to improve the bundle block adjustment, and hence the accuracy of the reconstruction (Nocerino *et al* 2013).

Lightweight fixed-wing SUA normally use lighter and smaller cameras than those available with other systems, as they generally have a smaller payload capacity. There are consequences arising from this limitation. Most of the cameras currently carried by fixed-wing SUA are in the compact point-and-shoot category and generally output JPEG files, although different cameras can be used with some of these SUA. For the reasons discussed in section 2.1.2 Resolution and sensor size, the quality of images from the default lightweight fixed-wing SUA cameras is generally less good, and the settings limitations imposed by flight control systems, which generally control the camera remotely for optimum exposure, mean that in some circumstances the image settings chosen are inappropriate for accurate results (Figure 70). In the example in Figure 70, the shutter speeds were too slow. Small fixed-wing solutions generally provide a less stable camera platform, because continuous movement at speed is required to remain aloft. Shutter speeds are therefore kept relatively fast to avoid blurring. In overcast conditions, this can lead to underexposed images. However, in most cases the images process well enough, and the products generated from them are of sufficient quality for many archaeological survey applications. Fixed-wing SUA can generally operate with wind speeds up to 65km/h (TSA 2015). Their great advantage is speed and efficiency of relatively wide-area coverage under the right conditions.


GCP Name: 1031 (369263.588,448136.880,212.933)

GCP 1031 was not marked in the following images (only up to 6 images shown). If the circle is too far away from the initial GCP position, also measure the GCP in these images to improve the accuracy.

Figure 70
Poor images taken from a fixed-wing SUA under windy conditions: GCPs shown.

Rotary SUA are more useful for subjects where oblique imagery is required. Rotary SUA are able to take oblique images as well as verticals. They are more manoeuvrable than fixed-wing solutions and can carry larger sensors, but are slower and have a shorter battery life. They are typically used for monitoring, inspection (Figure 71) and visualisation, but may also be extremely useful if significant vertical elements (sides of buildings, cliffs, etc) require recording, because these can be poorly represented in vertical imagery.

Figure 71
Image taken from a rotary SUA for wall-top inspection.
© Skyline Images

Rotary systems tend to be able to carry heavier payloads, and thus generally better cameras or other sensors. For imagery that is to be used for site presentations, a more stable rotary system is usually best and the acquisition of high-definition (4K and higher) video is possible; this can be processed photogrammetrically, as image overlaps are very high, although they may be subject to either or both motion blur and rolling shutter problems. Rotary SUA can generally operate with wind speeds up to 20km/h (TSA 2015).

In general, SUA offer several advantages:

- because of the lower altitudes at which they are flown, they can avoid some weather conditions that make photography from a manned aircraft difficult
- flying at lower altitudes also means that they can provide higher resolution mapping if required
- they are a fast and flexible means of acquiring data
- costs are relatively low for those recording discrete sites on a regular basis and there are many commercial operators competing for business if you are procuring survey.

For 'soft' detail (eg the edges of ditches and banks, which do not have unambiguous lines defining them), GSD smaller than 40mm is rarely useful in landscape archaeological contexts, although for 'hard' detail (subjects that have clear and unambiguous edges) it can be insufficient for cleanly resolving these edges, and in that case a GSD in the region of 10–20mm may be more appropriate. In most cases a reasonable compromise can be made given the size of the smallest detail that needs to be resolved, the size of the area to be covered, the computing power available to produce a result from the inputs generated and the required output scale. If you need to monitor change on a site over time, the GSD has to be sufficient to allow detection of that change, and the control network used should also be measured with an accuracy commensurate with the size of change you wish to detect.

Rotary SUA are the platform of choice for most building survey work where aerial images are required. Wall-top monitoring, inspection and measured survey all require a stable platform able to focus on the point of interest. Some SUA now come with collision avoidance sensors, which allows a constant stand-off from the subject to be maintained. This feature can be particularly useful for high-level building survey.

SUA are controlled and monitored from the ground. Most fixed-wing and some rotary platforms offer the option of pre-flight planning of the swaths to be flown and the frequency with which images are taken, so enabling a good enough overlap to ensure even and photogrammetrically reliable results and guaranteeing sufficient coverage of the site. The software solutions available to carry this out vary from manufacturer to manufacturer, but the principles remain the same. It is a good idea to enlarge the area of capture slightly when acquiring or procuring aerial imagery, in order to ensure that there is sufficient coverage of the site right up to, and slightly beyond, the edges. In the UK, beyond visual line of sight (BVLOS) flying of SUA is not currently permitted (in some European countries this restriction does not apply), which means that, with a line of sight restricted to 500m horizontally, the area that can be safely flown on any single flight is restricted to 1km^2.

Some of the occasional imaging problems with manned aircraft can be avoided by using an SUA. Haze, unless taking highly oblique shots, is not normally an issue because the flying altitude for SUA is capped in the UK at 120m above ground level (AGL) and photography taken from a SUA is below cloud level (if it is not, the pilot should not be flying the aircraft because visibility is compromised).

3.1.1.3 Kites and balloons

Kites and balloons have been used effectively for aerial photography for a long time. Both make efficient platforms for photogrammetric work and have been used successfully for archaeological purposes (for examples see Kite Aerial Photography). As this section is concerned principally with image acquisition, the special properties of kites and balloons are less important; the aim is to obtain results similar to those described for SUAs (particularly rotary platforms). A typical configuration of images taken by a kite (in this case to examine a roof structure) is shown in Figure 72.

3.1.1.4 Other sensors

In the last couple of years, lidar sensors that are light enough to be carried by SUA have come onto the market. These sensors can capture higher resolution lidar data than currently available from a manned aerial platform, and retain all the advantages of being able to filter point clouds (for example to remove tree canopies and derive a high-resolution DTM from the data). They also have the potential of integration with aerial photogrammetric data, in a similar fashion to its integration with terrestrial laser scanner data.

Ground-penetrating radar (GPR) sensors that are light enough to be carried by a rotary SUA are also now available. These require a flight height of approximately 1–1.5m AGL. They generally weigh about 1kg, and operate at a frequency between 500MHz and 1GHz, with a manufacturer's quoted ground penetration of approximately 2.5m, although this will vary with frequency. These sensors have not yet been evaluated by Historic England, but obviously combining data derived from such sensors with that from other sensors offers exciting possibilities for later analysis and interpretation.

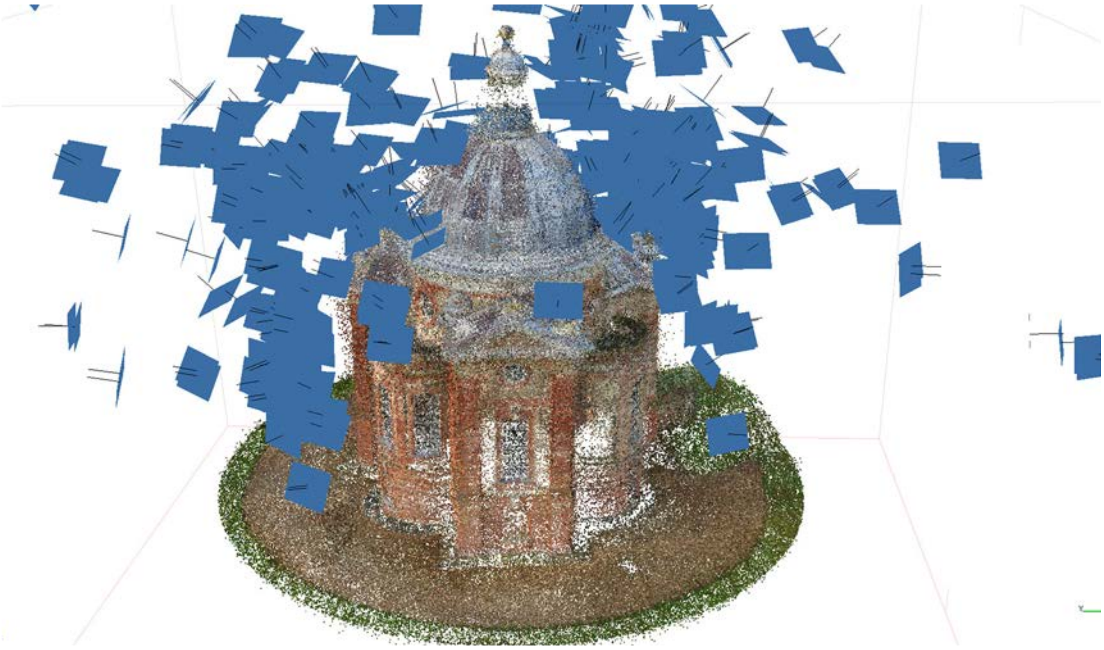


Figure 72
Image configuration taken from a kite.

Desktop scanners

Desktop scanners are cheap, easily available, and make it possible to scan photographic prints when negatives are not available. There are, however, some caveats to their use in a photogrammetric workflow. They are designed for non-photogrammetric users, and are suitable for general use as far as metric resolution (typically up to 1600dpi or higher) and radiometric resolution (8 or more bpp) are concerned. The geometric precision of desktop scanned imagery is, however, very poor (Calarco *et al* 2004; Mitrovic *et al* 2004) and brings with it the introduction of largely unquantifiable and variable errors in both axes in addition to the normal camera lens distortions already present in the prints. It is not therefore advisable to use a desktop scanner for scanning prints for photogrammetric purposes unless accuracy is not a high priority. They are, however, extremely useful if outputs commensurate with visualisation are all that is required. This holds true for the scanning of any prints, historical or otherwise.

The precision of different makes and types of non-photogrammetric scanners is very variable, and they exhibit both systematic and random errors, typically up to 1.1 pixels but with spikes of up to 3.5 pixels (Calarco *et al* 2004; Mitrovic *et al* 2004). Initially systematic errors may not seem to present too much of a problem, as theoretically they can be compensated for to some extent by calibration, where this is possible. This can require the use of a precision-etched optical glass plate to quantify the errors, but experiments have shown that even after calibration some systematic errors remain, demonstrating that the error pattern is not a simple linear one and is inconsistent between captures (Calarco *et al* 2004; Mitrovic *et al* 2004).

Photogrammetric scanners produce scans with error sigma values that are approximately 10 per cent of those exhibited by desktop scanners and have a random distribution. The errors introduced by a desktop scanner will therefore influence interior orientation estimates, thereby propagating errors throughout the photogrammetric workflow, adversely affecting the accuracy of the product and leading to high RMSE during, for example, aerial triangulation.

It is therefore advisable to scan negatives using a photogrammetric scanner; several makes are available, albeit at a cost, and if accuracy is a priority it might be worth outsourcing this element of the process. If scanning prints with a desktop scanner cannot be avoided, the probable effect on the accuracy of the product should be noted and made explicit in the project metadata. Also be aware that the print media, if not stored under good archival conditions, can become distorted, bringing another unquantifiable error source into play.

When scanning prints, it is obvious that a very high scanning resolution cannot produce a higher resolution product than the original image but will produce images

Figure 73
Aerial image with fiducial marks and other metadata.

that take longer to process. There is little to be gained by scanning prints with a photogrammetric scanner.

If you are procuring scans of prints from an archival source, remember to specify that the removal of fiducial marks or any other information from around the edge of an image is prohibited (Figure 73). These must not be cropped but masked on the inputs, as the whole of the input image is required to estimate the lens distortion characteristics.

A single mask can be used across all the images provided the inputs are consistent in their offsets; this can be a problem with images scanned from prints, which will therefore have to be masked individually. Some archives do not allow the use of scanners but do allow photographic prints to be re-photographed; this is an option but will of course bring in its own distortions. Prints should be re-photographed square-on using the longest focal length lens possible.

3.1.1.5 SUA regulatory framework

All commercial SUA operators in the UK must hold a valid CAA Permission for Aerial Work licence. In order to get this, SUA operators must undertake one of a number of approved training courses, gaining either a Basic National Unmanned Aircraft Systems Certificate – Small (BNUC-S) or a Remote Pilot Qualification – Small (RPQ-S) for their specific SUA type. Once this has been achieved, a company must additionally submit an SUA operations manual for each of its aircraft (which must be re-submitted annually) and an SUA technical manual to the CAA, along with an annual fee. The CAA categorises SUA by weight, with different classes having different restrictions on when and where they can be flown; separate permissions are required for flying heavier SUA, and they require more experienced operators.

Non-commercial operators (those who undertake work without accepting ‘valuable consideration’ for it) still need to be aware that safe and responsible operation is paramount and a legal requirement. An SUA can be heavy, moves at speed and has the potential to cause considerable harm or damage if control is compromised in any way.

All operators should ensure that they have adequate insurance before they undertake a flight. Insurance premiums vary, and the growth of the technology has meant that more insurers are moving into the SUA market. Insurance premiums are in general affected by operator experience, annual hours flown and the environments in which the SUA are typically operated. In addition, permission must normally be sought from the landowners. Permission must be sought before low-level flying over all English Heritage properties.

SUA regulations in the UK are in the process of change: for the latest information, visit the CAA website. Historic England does not and will not use contractors that are unable to demonstrate that they hold the appropriate CAA permissions and public liability insurances, and who have not undertaken a full risk assessment and method statement for a planned flight.

3.1.2 Analysis

The most often used product in archaeological landscape analysis is a DEM, usually in conjunction with an ortho-image. There are many ways of pre-processing the point cloud data to provide a DEM for archaeological landscape analysis. Some photogrammetric software allows the data to be filtered to remove buildings and trees. This is often not based on characteristics encoded in the data, as may be the case when dealing with full-waveform lidar data, but carried out by dividing the dense point cloud into a series of ‘cells’, making a local search of those cells to establish a likely ‘ground’ level and filtering out data in any particular cell that does not conform. Vertical intervals between the ground surface and other data can be specified to enable the removal of, for example, tree canopies or roofs. The more laborious process of manual classification is an option, in which case points are selected by hand and assigned a class. This is often the easiest way to identify water bodies, for example. More sophisticated products, such as Erdas Imagine, are able to undertake more complex classification of photogrammetric point cloud data based on a variety of characteristics, including colour.

In the case of medium to large areas, commonly the subject of landscape investigation, the products are most effectively dealt with in a GIS, which will typically involve exporting the 3D data from photogrammetric software as a raster image. It is often economical to use a specialist viewing package such as QT modeller, or a visualisation toolbox such as RVT, as an intermediate step. While these softwares are aimed at those using lidar data, visualisations can often be done more quickly outside a GIS and then imported as 2D raster images for further processing. GIS is commonly used not only because of the analysis that can be performed on the DEM, but because it allows integration of the photogrammetric output with spatial data derived from a large number of other sources, and examination of the interactions between these data.

When exporting to a GIS, remember that the raster image (DEM) is a regular gridded format in which each pixel is usually square and represents a regularisation of the more randomly distributed dense point cloud or the nodes of the mesh from which it is derived (usually, in its raw form, a TIN). While this is not normally problematic, it does involve a small amount of smoothing in a similar way to that involved when processing lidar data into raster images (*The Light Fantastic: Using Airborne lidar in Archaeological Survey*). While a TIN may be imported into a GIS, and it has the advantage that the data is not interpolated to the same degree, TINs are generally more difficult to process and typically require conversion into a raster surface before second-order derivatives such as hillshades can be extracted or other forms of analysis undertaken. A useful summary of the advantages and disadvantages of dealing with point cloud and raster surface data is given in (*The Light Fantastic: Using Airborne lidar in Archaeological Survey*, 11). Most off-the-shelf commercial photogrammetric software packages permit the export of a DEM as well as the TIN, and a DEM can be produced in an open-source workflow by passing the dense point cloud or mesh to a separate piece of software such as Meshlab or Cloud Compare, for scaling, orientation and export in an appropriate format for further analysis if required. Both of these examples of software have a range of powerful analytical filters that can be used if a GIS is not available.

Perhaps the most accessible and obvious ways of using GIS to extract useful archaeological information from the DEM are hillshades, slope analysis, contouring and, when there is more than one data set available for comparison, principal component analysis (PCA), although many other ways of dealing with such data are available. At Historic England, the analyses mentioned have proven to be the most fruitful outputs for field teams to use, largely because they are relatively straightforward to achieve for non-GIS specialists and show the data in a readable and interpretable fashion. These analyses can be undertaken in most GIS, both commercial (for example ESRI's ArcGIS) and open-source [for example QGIS, GRASS, the Lidar Visualisation toolbox available from the Arcland website and the popular Relief Visualisation Toolbox (RVT). The resolution of the outputs chosen is dependent upon several factors, including the resolution of the inputs (that is, the GSD), the size of the smallest details that require representation, and maintaining usability of the data: a large area covered at high resolution can generate enormous files quite quickly, and hardware limitations may mean that the outputs have to be broken down into a number of smaller, seamless raster tiles to allow reasonable processing times, especially on less powerful computers.

While it is sometimes useful to increase the resolution of DEM beyond its native GSD, it is fruitless to increase the resolution of an ortho-image beyond this: you would simply be increasing the number of pixels in the output without a corresponding gain in resolution. If you do increase the resolution of a DEM for output, bear in mind that intermediate points will be interpolated from surrounding values and that, without the use of breaklines, this can also introduce smoothing into the raster grid. Whether this is acceptable or not will vary in different situations and with the type of detail or variation you are attempting to resolve.

At higher resolutions you should also consider that variations in vegetation can produce noisy data: with a GSD of *circa* 40mm, variations in the length of grass over a site can have a significant and possibly detrimental effect on the DEM. This sort of noise is reduced considerably with increased flight height, and is almost never an issue with photography acquired from a manned aircraft because such very small details are rarely clearly defined. As mentioned in section 2.1.9 Multispectral imagery, these variations can sometimes be useful, especially with regard to crop heights, for identifying potential archaeological features, although their causes can be manifold and care should be exercised in their interpretation. Differences in grazing regime, for example, may mean that one part of a field has shorter grass than another, and particular care should be taken when comparing DEMs of the same place from imagery shot at different times of year. It is also worth noting that vegetation heights can have a significant effect if you are integrating or comparing a photogrammetrically derived DEM with a lidar-derived one: the photogrammetric model will often appear raised above the height of the lidar model, this difference being a function of vegetation height, which is usually filtered from lidar data (Green *et al* 2014).

Out of the box tools are available in most GIS for performing slope, hillshade, contour and PCA analyses of DEM data. Other, more complex methods of analysis are possible, but for rapid interpretation those listed here provide a sound basis. Usually, a combination of products, strengthened with a high-resolution ortho-image, provide the best starting point for extracting useful interpretative archaeological plans. For landscape work, the workflow that has proven to be most effective is as follows.

- Office: preparation, research.
- Field: reconnaissance, including full field walkover and formulation of initial interpretation.
- Field: image acquisition.
- Office: image processing, DEM and ortho-image production.
- Office: GIS-based analysis and generation of interpretation aids such as hillshaded DEMs.
- Office: vectorisation (and hence interpretation) from these outputs, usually as top and bottom edges of slopes or feature outlines.
- Field: checking of analytical outputs, refinement of linework, refinement of interpretation.
- Office: production of finished interpretative illustrations based on revised outputs.

This workflow is explained with reference to a real site in case study 2.

The importance of reconnaissance cannot be overstated, and serves several purposes. For the archaeologist undertaking the interpretation, it is an opportunity to become familiar with the site and to start the process of understanding the features that are visible, the stratigraphic and temporal relationships between them and their spatial and cultural context. It is also an opportunity to assess potential safety issues that should be communicated to the subcontractor (if one is used), to consider where GCPs may be most usefully placed, to consider the extent of the area that will require coverage, and to decide on the necessary GSD to resolve the required detail successfully at the desired scale of output.

Large, repetitive linear features, for example ridge and furrow, land drains and stratigraphically straightforward or discrete features, can be mapped directly from the DEM rather than in the field, although a degree of field verification is necessary. This method can save a great deal of time for field surveyors who would otherwise have to map these with GNSS; they can then devote more time to interpreting more ambiguous or complex areas. Aerial imagery can also be used to record detail in areas that are not otherwise accessible (for example on military ranges), although care should always be taken to secure and observe access rights and respect rights to privacy, etc.

The process of digitisation from a DEM and slope analysis in CAD is shown in Figure 74. Firstly, field drains and water courses are added. Next, top and bottom edges are digitised, followed by hachures to make the slope direction clear. In the final image the underlying hillshade of the DEM has been removed for clarity. The linework is now ready for field revision followed by the production of the final interpretative drawing.

For aerial reconnaissance work, it is often sufficient to produce an ortho-image alone rather than a DEM, simply to locate the feature(s) correctly and allow its digitisation and interpretation.

3.2 Terrestrial photogrammetry for buildings and structures

The SfM–MVS workflow provides most of the advantages of traditional photogrammetric products for the survey of buildings and structures with the addition of new benefits. SfM outputs are sometimes used on their own but, like the data surveyed by other methods, are usually a means to an end and need conversion into a useful product. The most commonly used products in the recording and presentation of buildings and structures are ortho-images and 3D models. DEMs and products useful in other areas are less often

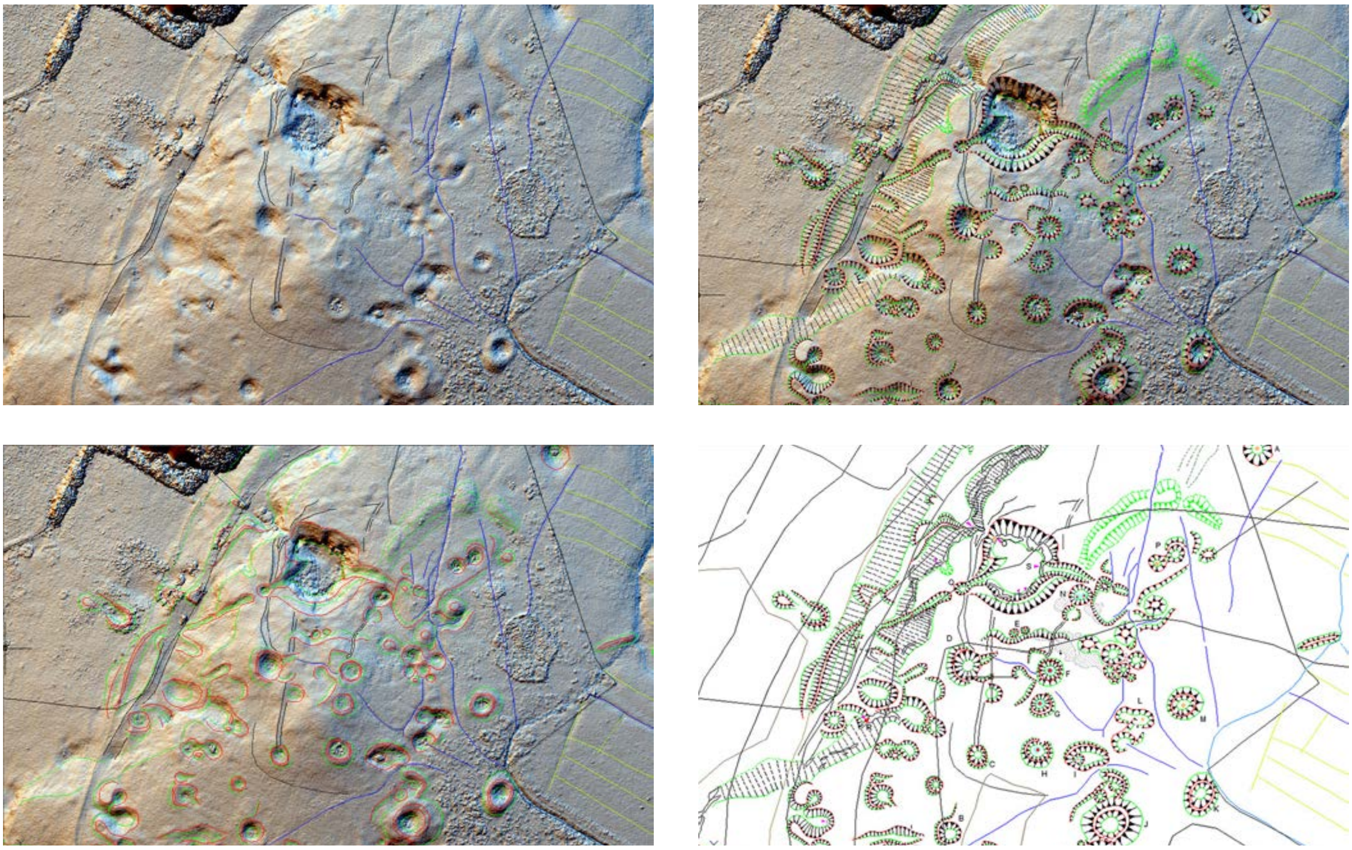


Figure 74
Digitising archaeological interpretation from DEM and slope analysis.

employed unless assessing a relatively localised deformation; more general deformations can be assessed via analysis of the full 3D model.

3.2.1 Ortho-imagery

A scaled ortho-image derived from photogrammetry can be used as the basis for:

- tracing 2D linework in CAD
- as a product in itself (providing a metric record of materials, condition, colour and arrangement, including defects such as cracks)
- a combination of the two.

The point densities required from SfM-generated data for ortho-photographic processing, at least that procured by Historic England, are given in Andrews *et al* (2015). Because ortho-image production is contingent upon having a DEM, the accuracy of which will determine the accuracy of the ortho-image, the spacing of points required in the DEM to be used for generating an ortho-image, and the maximum permissible GSD at the same scales, is given in Table 4.

Output scale	Maximum point spacing	Maximum GSD
1:10	1mm	1mm
1:20	5mm	2mm
1:50	10mm	3mm
1:100	10mm	10mm
1:200	20mm	20mm
1:500	40mm	40mm

Table 4

In practice, given the high resolutions that can be obtained with most modern cameras, these GSDs will usually be exceeded.

One important difference between the data derived from tracing linework from an ortho-image and a traditional photogrammetric output is that the ortho-image-derived linework will be 2D only. For true 3D linework, detail must be traced directly from the 3D model, and few, if any, SfM–MVS-based packages allow this at present. In most cases, however, this does not present a problem because the most commonly disseminated outputs from archaeological building survey still focus on a ‘flat’ 2D product, presented as hardcopy or in a .pdf or CAD format.

There are alternative methods for producing 3D linework as output (which was a standard product with stereo photogrammetry), and these usually involve importing the dense point cloud into software more commonly used for 3D laser scanner data (or indeed many CAD packages) and digitising the detail using those means, although some software dedicated to this task is available. All of the problems usually associated with digitising from point clouds remain, and it can be a lengthy and difficult process to get the process right with complex geometry, although there will be a large number of high-quality reference images to resolve points of doubt.

Recording the exterior of a building photogrammetrically is faster in the field than using the more ‘traditional’ combination of a TST and hand measurement, but this is to some extent compromised by the extra time required in the office to produce the ortho-image (and digitise from it if required), as well as less time spent in the field looking at, and understanding, the subject. The amount of time saved generally increases with scale; you will save more time overall if you are required to produce drawings at 1:20 than at 1:200, because the frequency with which measurements must be taken with the TST would be greater, and it is far easier to digitise from the ortho-image in CAD at the required intervals than in the field). For accurate work a TST can be used to add control measurements, usually to easily identifiable points of detail on the elevations (for example corners of windows and ventilation grilles). The TST is invaluable if you plan to integrate more than one elevation in the same coordinate system, or if the elevation has significant projecting detail (for example porches and colonnades). Control points and their distribution are discussed in section 2.3 Control.

Detail that cannot be seen in the input photography cannot be accurately reconstructed in the photogrammetric model. Thus it is important to ensure that the tops of sills, bay windows, etc, are recorded in some fashion, even if by hand measurement on a few examples, which can then be incorporated into the final drawing if line output is required. If the ortho-image is to be the product, a way of filling any gaps must be found (by taking imagery that covers them) or their presence indicated (Andrews *et al* 2015). As with all methods of drawing production, one single survey technique will rarely provide all the information required for a finished product.

Figure 75
Images of the same elevation taken from the same standpoint using lenses of different focal lengths.

3.2.2 Elevations

Recording a single building elevation is perhaps the most straightforward use of photogrammetry. In general, the best approach is to attempt in part to mirror the aerial application of the process, by providing a series of overlapping images covering the entire elevation from left to right, bottom to top, but braced with additional oblique images. If nothing else, a methodical approach encourages completeness of coverage (see section 2.2 Image arrangement). This is most easily achieved, in the case of smaller buildings (less than three storeys), by using a combination of photographic tripod (for the ground floor) and a mast at different heights (for the upper floors). Care should be taken to ensure that there is enough side lap between the runs to allow their relative positions to be computed successfully. In many urban situations, the narrowness of streets means that stand-off is compromised. In such situations the use of a wider angle lens (for example 18 or 24mm) can be helpful, as fewer shots need to be taken. Figure 75 shows an example of the field of view of 24mm and 50mm lenses from same position. Roofs, however, can still present a problem. Common workarounds include:

- increasing the stand-off and using a zoom lens to fill in any roof detail not visible from the ground
- if the stand-off cannot be increased, attempting to see as much of the roof as possible by moving to the sides and taking fill-in photography from there
- arranging access to a building opposite and taking the necessary photographs from its upper floors or roof.

In some cases it may only be possible to record the roof properly using a TST or hand measurement, either by gaining access to the roof itself and surveying it separately (but in the same coordinate frame as that used for the photogrammetric recording of the main elevation) or by surveying significant features (rooflines, chimneys, plants, etc) from the ground if they are visible. This may also be necessary in the case of very tall buildings fronting onto narrow streets. Highly oblique measurements with a TST, although undesirable, may be necessary as they are likely to be more accurate than those derived from photographs. Points on roofs taken with a TST can also be used as photogrammetric control if sufficient image coverage has been obtained. In a more rural or open setting, infill photography of roofs taken from a SUA or kite can provide the best means of obtaining the necessary data to complete the photogrammetric model without additional use of the TST. In urban environments, special permissions are required to fly SUA and road closures may be deemed necessary.

Where more than one exterior elevation is to be recorded, the best results are achieved if a single control network is established around the building (using a TST), thus allowing all of the elevations to be recorded in a common coordinate frame. This also makes the process of drawing production in CAD considerably easier.

Interiors are more easily dealt with, and very good results can be obtained in most circumstances provided there is sufficient light (see section 3.4.2 Lighting). When photographing wall paintings, for example, use of colour reference cards is essential. Do not forget to photograph the floor as well, if possible, or the model will remain incomplete if it is required for visualisation purposes.

3.2.3 Problem areas

Certain sorts of detail (notably decorative ironwork) will usually reproduce poorly in a SfM-derived model and ortho-image. The general positions of such objects will be visible but the overall model will usually be incomplete (Figure 76). Fill-in photography focusing on the problem area is one potential solution but, if a line drawing is the desired product, it is usually best to record such things using hand-measured sketches, draw them up in CAD and add them to the drawing in the appropriate position using the ortho-image as a guide. Complex curved metalwork structures, especially those that are highly specular or coated with glossy paint, will also model poorly; for such cases you will need to use a different method of recording.

Figure 76
Poor representation of ironwork in an ortho-image from general shots of an elevation.

Figure 77
Extraneous geometry produced when photographing windows.

Glazed windows can also be problematic, and usually produce large numbers of extraneous polygons in the final model, resulting from both reflections and objects visible through the window (Figure 77). If possible, it is often better to mask windows out of the input photographs before processing; the necessary detail can be added to the final drawing later by other means. If masking is not an option, extraneous points should be removed manually from the dense point cloud before generating a polygon mesh, if that is required. If you do not manually edit the dense point cloud, but set an upper polygon limit for the model when you generate a mesh, a considerable number of the polygons generated are likely to be ‘junk’ data associated with reflections, etc; these will have to be deleted, which will mean that you have fewer polygons from your ‘budget’ representing detail that is of interest.

Figure 78
Masking sky in input images to reduce extraneous geometry at the processing stage.

In a similar vein, if possible it is usually worth masking out the sky from the input images before processing. Not only does the sky have no useful points for matching images together, it can also generate large quantities of extraneous geometry that require subsequent removal in a similar fashion to glazing-related artefacts (Figure 78).

3.2.4 Integration with 3D laser scanning

Point cloud data derived from photogrammetry can be integrated successfully with data generated by a 3D laser scanner ('hybrid modelling') if that satisfies the metric requirements of the project and is on the same control system. It is often possible to obtain photogrammetric data from areas where it is not possible to get a line of sight from a scanner, for example by using a camera on a photographic mast. There is a lot of software available for the processing of point cloud data derived from scanners and it is beyond the scope of this guidance to detail them all. One issue to note, however, is file formats. Many packages designed to deal with terrestrial scanners can now import the ‘universal’ E57 format; prior to this, nearly all scanner manufacturers only used proprietary formats, which meant that merging data could be problematic. Some photogrammetric packages do not currently permit the export of point cloud data in the E57 format, but instead use formats useful for other, largely visualisation focused, purposes (for example Wavefront .obj and Stanford .ply). They do usually permit export in a lidar .las (or .laz) format, as many of them are focused on aerial mapping, which can be useful if you are planning to integrate your aerially derived point clouds with lidar data.

As described elsewhere, data derived from the scanner can be used as a control for the photogrammetric data. Some software packages, for example RealityCapture, are now able to integrate scanner data directly with photogrammetric data. This uses the data from both inputs and combines them into a fully integrated product derived from both sources. If you are not able to use such a package, it is possible, in Agisoft Photoscan Pro, for example, to process the laser scanner data in a separate software package (for example FARO Scene or

Leica Cyclone), export a model, import it to the photogrammetric package, and texture it using the (previously aligned) high-quality images from a better camera than that provided on the scanner. The data from both sources needs to be registered accurately in the same coordinate frame. This processing workflow can be useful because most terrestrial laser scanners are poorly equipped with regard to cameras and textural information is therefore often lacking.

3.2.4 Tripods

A photographic tripod is an essential piece of equipment for terrestrial photogrammetric imaging. By stabilising the camera, smaller apertures (and hence greater depth of field) are possible because they can be compensated for by using longer exposure times, if external lighting rigs are not available, for optimal exposure. A tripod should be used as the default, and hand-held use of the camera resorted to only when necessary. If shutter speeds slower than about 1/60second are used, a tripod is required to avoid blur. The extra time taken moving the tripod around is more than compensated for by the increased chances of obtaining sharp images, which will always process better and give a superior product.

3.2.5 Mast or extendable tripod

As normal photographic tripods are only helpful up to the height of the photographer using them, other solutions may be necessary in terrestrial photogrammetry to raise the camera higher, for example by using masts or extendable tripods (Figure 79). The first rule with using a mast for photography is to do so safely. Keep away from power lines or other obstructions, and do not use it if you are unsure about your ability to control it in windy conditions. Keep well away from windows if possible. It is usually best to have two people available for hand-held mast photography, thus reducing the chances of a slip that can have unpleasant consequences for the subject of your photography, yourselves and/or your equipment.

If you are using a mast, you do not require an ordinary pan and tilt photographic head (commonly used on tripods), as panning can be undertaken by twisting or moving the mast. A simple tilt head greatly reduces the weight at the top of the mast and is cheaper. Using lighter cameras is also desirable, although not always possible.

Use of a mast (typically constructed from glass fibre, aluminium or carbon fibre) means that there is movement of the camera at the top of the mast, especially under windy conditions. If possible, therefore, try to avoid shooting in very windy conditions, and even under calm conditions

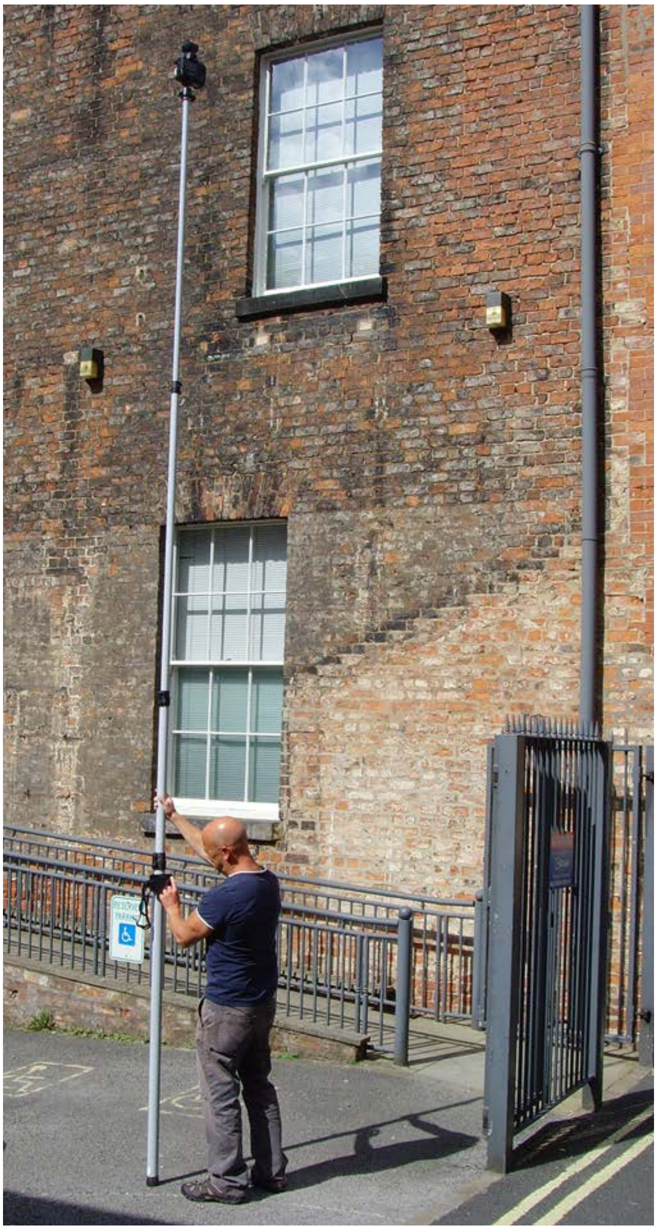


Figure 79
Use of an extendable photographic mast.

keep the mast as still as possible and allow the vibrations caused by moving it from one location to the next to settle before taking photographs. Faster shutter speeds will be required to avoid blurring images using this method, because of the inherent instability; masts are usually hand-held at the base, but even if mounted on a vehicle or sturdy ground anchor there will still be movement at the top except on the calmest of days. It may be necessary to run the camera in shutter priority mode, and select a shutter speed of 1/60 second or faster if conditions allow.

As well as providing a more stable base, vehicle-mounted masts can be much taller than hand-held ones, and are typically raised and lowered hydraulically or using an electric motor, which considerably reduces the amount of physical work needed to use them. Faster shutter speeds can be compensated for by using wider apertures, so faster lenses (those that will open to wider apertures, thus letting in more light) are often desirable, especially in low-light conditions. You need to be aware of the corresponding reduction in the depth of field, but this is not usually an issue given the stand-off from the subject that can be achieved. Hand-held masts usually cover a range between 5 and 12m, after which they can become unmanageable, while vehicle-mounted masts can extend the range to 40m.

Masts are extremely useful for a number of applications. For subjects that are more or less at ground level (for example dwarf walls and archaeological excavations) the photographs they provide can easily be used to generate an ortho-image, which is difficult to derive from more oblique photography taken from ground level. In addition, the area covered by each image is larger, so in most cases fewer images are required. The ortho-images can be used partly for the derivation of vector plans, by taking the ortho-image into CAD or GIS software and digitising detail from it. Although true vertical shots are impossible (the mast itself gets in the way), near-verticals can be taken, and the use of L-plate adapters, which allow the camera to be orientated in either portrait or landscape mode, can be helpful. In building survey, at least of smaller structures, masts can be used to provide shots that fill in detail that is not visible from ground level.

Figure 80
Rain sleeve on a camera for use in wet conditions.

A remote trigger for the camera is essential when using a mast, and a number of different options are available that vary considerably in functionality and price. The Camranger, for example, gives you full control of the camera settings while it is aloft, uses the camera's live-view to show what the camera is pointing at, and can be controlled using a mobile phone or tablet at ground level via an app (this works for both Android and iOS as well as on a laptop); it works with most popular DSLRs. Other similar solutions are available. Many camera manufacturers offer their own apps for products that offer similar capabilities (Sony's PlayMemories Mobile, for example, can be used with their popular Alpha 7 range of cameras, and offers control of some functions of the camera via a mobile app). Communication between camera and ground unit is typically via a wireless network connection between the two. There are many other solutions that offer a wireless remote shutter capability, which can be useful under some circumstances, although being able to preview an image is not always possible and control of camera settings can be problematic. Having to change camera settings manually can take some time when using a mast, as the camera has to be brought back down to ground level for the adjustments, and this can be particularly frustrating on days with changeable weather conditions. When using a mast on wet days, a rain sleeve or cover for the camera (Figure 80) is a worthwhile investment (many are available), as is the use of a lens hood to minimise water droplets getting onto the lens.

3.3 Terrestrial photogrammetry for excavations

Provided the principles outlined in other sections are adhered to, the potential applications of photogrammetry for archaeological excavations are many. SfM–MVS approaches offer a more affordable method for 3D recording than terrestrial laser scanners, record colour and textural information better, are faster to acquire and provide outputs of a suitable accuracy (Doneus *et al* 2011; McCarthy 2014; see case study 6). In common with other mass-capture data acquisition methods, however, the outputs are metric but still require interpretation, unlike, for example, a hand-drawn section, which transmits the interpretation through the process of selection at the point of capture.

Archaeological excavations are generally visually texture-rich, and matching images is not usually problematic. Wet surfaces or puddles on a sunny day are likely to reflect light and appear shiny, so under these circumstances matching can be compromised or noisier data produced. Puddles should, as in the case of ‘traditional’ site photography, be removed before imaging if possible.

Perhaps most usefully, ortho-images offer an excellent means of recording plan information, especially when footfall across an area should be minimised. The delicate and complex wooden platforms at Star Carr, North Yorkshire have been recorded using this method over the last few years (case study 5) as well as, for example, recent excavations at Must Farm, Cambridgeshire. The GSD achievable (even using a photographic mast) with a reasonable digital camera is more than adequate for recording at a scale of 1:20 or smaller.

As with building survey, an ortho-image provides an excellent representation of colour, texture and relationships between features, can be easily incorporated into a GIS or CAD system for generating plans, and can be digitised to derive vector outputs. Sections can be recorded in this way. Similarly, DEMs can be used, for example to map deformation in mosaic floors (Green *et al* 2014). 3D textured mesh models of particular features or areas of a site can be very useful: a model of a site can be sliced to provide profiles in any orientation. In all cases, comprehensive coverage is key and a methodical approach is advised. Use of an accurately measured common control system will allow you to combine the results from adjacent or overlapping trenches excavated at different times into a single model, allowing the spatial relationships of objects and areas not seen at the same time to be appreciated in three dimensions. Taking repeated photogrammetric surveys as an excavation progresses enables the composite reconstruction of layers, allowing, for example, virtual sections to be generated.

You should include a colour index card and/or grey card in the images, and you will need to re-shoot if lighting conditions change during the photography, to enable a reasonably consistent output. Control is usually measured with a TST, and will therefore be accurate to within ±3mm (reflectorless) at ranges typical for archaeological sites. As for other applications, the control can be used to both refine the orientations of the cameras and to provide absolute orientation for the model with respect to the site coordinate system. If using SfM for an archaeological site or feature without a TST to provide control, it is essential you include scale bars in the images. A small amount of forethought means you can produce models that are not only visually pleasing but also metrically accurate.

3.4 Terrestrial photogrammetry for smaller objects

The principles that must be applied when imaging smaller objects are the same as for larger objects, but some of the equipment and techniques that can be used will vary.

3.4.1 Macro lenses

True macro lenses provide a magnification factor of at least 1 (or a scale of 1:1) at their closest focus setting. This means that, at a scale of 1:1, the object will appear on your camera's sensor at the same size as it is in real life. Magnification is determined by the focal length of the lens and the focusing distance: the closer you can focus, the more magnification a lens of given focal length will be able to achieve. Macro lenses are capable of much closer focusing distances than ordinary lenses to achieve this magnification; if you are using an ordinary lens, you will be well inside the minimum focusing distance for your lens before you can achieve a reproduction ratio even close to 1:1.

Different focal lengths of macro lens are useful under different circumstances: generally, longer focal length lenses allow a greater stand-off from the subject; thus, for example, a 40mm or 60mm lens allows you to get very close to a subject, while a 200mm lens allows you to have a reasonable distance between the lens and the subject with the same result. With photogrammetric use of macro imagery, the main practical difference is that a longer focal length lens allows more lighting to be placed between the camera and the subject, which can be useful for the reasons outlined.

One characteristic of macro photography, and the main issue when using it photogrammetrically, is that the depth of field tends to be very shallow at 'normal' apertures. Thus, for example, when using a 100mm macro lens at f/2.8 on a camera with an APS-C sized sensor, the depth of field is approximately 0.6mm: only those parts of the subject that are 0.3mm in front of or behind the focus point will be sharp (in macro photography the depth of field remains symmetrical about the focusing distance). Decreasing the aperture to f/11 extends the depth of field to approximately 2.6mm. Smaller apertures will increase the depth of field further (but at a cost). It is therefore best to use a tripod, focus macro lenses manually and use the live view, if available, to refine the focus point.

A shallow depth of field is much less of an issue when shooting a largely planar subject: purpose-built macro lenses are 'flat-field' lenses, so the centre and edges of a subject that is planar will all be in focus. Most small objects that you want to model, however, will not be planar. Several workarounds are available to reduce the impact of a shallow depth of field, but not all of those useful to, for example, a wildlife or product photographer (such as focus stacking or other image manipulation techniques) are suitable for photogrammetric purposes. All workarounds involve some compromise.

Decreasing the aperture: 'stopping down', or reducing, the aperture (to, for example, f/16 or f/22) has the net effect of increasing the depth of field but will also, after a certain point, cause a loss of sharpness as a result of diffraction (the 'diffraction limit'). Stopping down also requires much slower shutter speeds to compensate for the lack of light reaching the sensor, higher ISO values, or the use of external lighting.

Arranging the subject so that it is as parallel to the sensor as possible: subjects that are long and narrow will not image well if shot from either end. Most of the subject, given the shallow depth of field, will be out of focus (Figure 81). It makes sense, therefore, to arrange the subject as close to parallel to the plane of the camera sensor as possible in each shot, allowing most of the subject to be in focus in each image. In practical terms, this involves rotating the subject about its long axis while it is being photographed.

Increasing stand-off: this has the effect of lessening the magnification at the expense of having the subject fill less of the frame. This works for applications of macro photography where an image can be cropped for presentation purposes; for photogrammetric imaging it has the effect of reducing the resolution achieved but it can provide additional background areas that can be used for image matching. The required resolution of the product will have a bearing on whether this workaround is acceptable or not. External lighting can be used with increased stand-off.

Using a different camera: cameras with smaller sensors can achieve better results with regard to frame filling, depth of field and effective detail when imaging small objects, albeit at the expense of all the factors mentioned in section 2.1.2 Resolution and sensor size. In common usage, the term ‘macro’ is often used to describe close-up photography, rather than ‘true macro’ photography. In close-up photography, magnifications of 1:10 or so can be achieved and the subject can still fill the frame. The size of object that can fill the frame is dependent on the sensor size of the camera used: the smaller the sensor size, the smaller the object. Thus an object imaged at 0.5× magnification will occupy less of a full-frame 35mm sensor than the much small sensor of a compact camera, so, effectively, a smaller sensor allows smaller objects to fill the frame. The magnification factor achieved is often expressed as a 35mm equivalent magnification for smaller format systems. The depth of field is increased when using smaller sensors at the same magnification; the smaller sensors on compact cameras offer an increased depth of field over full-frame 35mm cameras, and this can be a significant advantage, although tempered to some extent by the slightly reduced image quality in other areas.

3.4.2 Lighting

Given the small apertures that often need to be used, lighting is important when imaging very small objects. Even lighting is as essential when imaging smaller objects as larger ones. For very small objects, a ring flash unit can be extremely useful and is not necessarily expensive. LEDs can provide a very cold light, and the white balance should be adjusted accordingly. A colour index card should always be included, in one shot if the lighting conditions remain consistent and in more than one if the lighting conditions change. If a ring flash unit is not available, a flash unit attached to the hot shoe of the camera can be used; a flash diffuser should then be employed, and it is often useful to point the flash unit away from the subject (for example upwards) and bounce the light from a reflective surface to provide more even lighting. If possible, the best option is to use external or studio lighting.

Figure 81
Shallow depth of field causing problems with the ends of ‘long’ objects in macro photography.

Setups more commonly associated with product photography can be used, such as light tents. The object is placed inside the tent for imaging and lights are used outside the tent, which scatters the light, allowing diffuse and even coverage if a number of lights are used (Figure 82).

3.4.3 Turntables

Turntables can be used with small objects to allow the camera to remain relatively static while the subject is revolved between each exposure, generating the effect of circling the subject with the camera. Specialised photographic turntables are available, but in practice turntables designed as a cake stand (a ‘Lazy Susan’) can work just as well provided they are stable and the object not too heavy. This method can shorten the image capture phase considerably because the object is moved rather than the camera. It is advisable to shoot more than one ‘ring’ of shots round the subject, for example by increasing the camera height for each ring (Figure 83 shows an example of an image arrangement; see section 2.2 Image arrangement). Backgrounds should be kept as neutral as possible.

Figure 82 (top)
Use of a product photography tent for lighting small objects evenly.

Figure 83 (above)
Use of a turntable for imaging small objects.

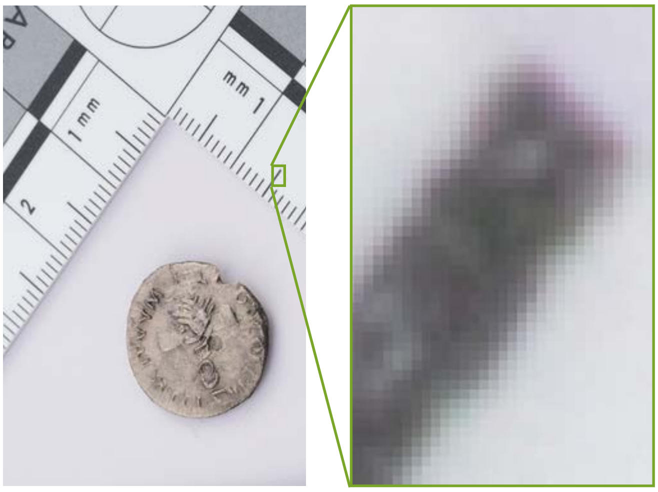


Figure 84
Scale bars photographed with a high resolution camera.

Control for small objects is discussed in section 2.3. If you are using a fine gridded film placed under the subject, it should be clearly visible in all images; if you are using scale bars, make sure you include them in sufficient images. Given the very high GSD achievable in macro or close-up imagery, bear in mind that on some scale bars the width of the graduations on the scale itself can be many pixels wide (Figure 84), placing a constraint on the accuracy with which the object can be scaled. Callipers often have much finer graduations than scale bars, and make an excellent alternative if available. Alternatively, as discussed in section 2.3.2 Sources of control data, coded targets or scale bars can be used.

When modelling an object in full 3D, it is often necessary to capture the upper and lower surfaces separately, with sufficient overlap between the two, and merge the parts later to form a single model, as discussed in section 2.2 Image arrangement. In some cases, an additional set of imagery covering the overlap, and common to both sections of the model, can ameliorate the effect of noisy data at the edges of each half. This noise is typically the result of a loss of focus (because of a shallow depth of field) towards the edges of the models, creating a ‘seam-line’ where they join (Figure 85) if this is not rectified by additional imagery. Use of mirrors to image inaccessible areas of subjects (Mallinson and Wings 2014) is not advised because the geometric properties of the image are compromised. Alternatively, defects at the joins can be removed using external mesh editing software, but with a consequent loss of reconstruction accuracy in that area of the model. It is often necessary to use distinctive points on the objects themselves to match between different models if there is not sufficient overlap between the two for an automatic tie point-based alignment from the input imagery.

Making models of small objects photogrammetrically can be time consuming, especially at the image capture phase. While this is usually not problematic with one or two objects, it is worth considering whether an alternative approach would be more economical if large numbers of small objects are to be modelled. High-resolution 3D laser scanning, for example, is not affected by depth of field issues, and for collections of objects such as bones, arranging access to a computed tomography (CT) scanner, if possible, can be a more fruitful approach, albeit offset by considerations of cost and a lack of colour texture.

3.5 Textured 3D models

Objects are the most common subject that requires a 3D textured model. If the desired output is intended primarily for visualisation purposes, the metric requirements of the model can be lower than those required for other purposes. A well-designed workflow for dealing with the data should ensure accuracy throughout the process, but the polygon counts in the final models can probably be reduced drastically in order to reduce file size, and so aid transmissibility and accessibility. Reduced polygon counts can often be ‘disguised’ by the effective use of good-quality textures.

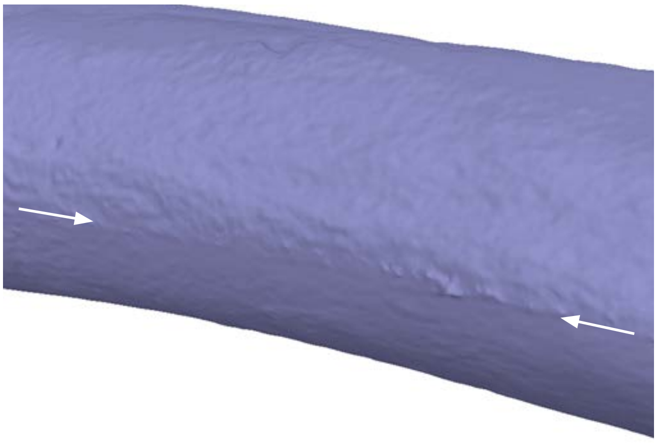


Figure 85
‘Seam’ lines appearing in a model where there is insufficient overlaps between halves.

There are many other ways of disseminating 3D model data. For email distribution, 3D PDFs are popular and allow other users without access to sophisticated 3D software to view, label, section and measure low-resolution 3D models (Figure 86).

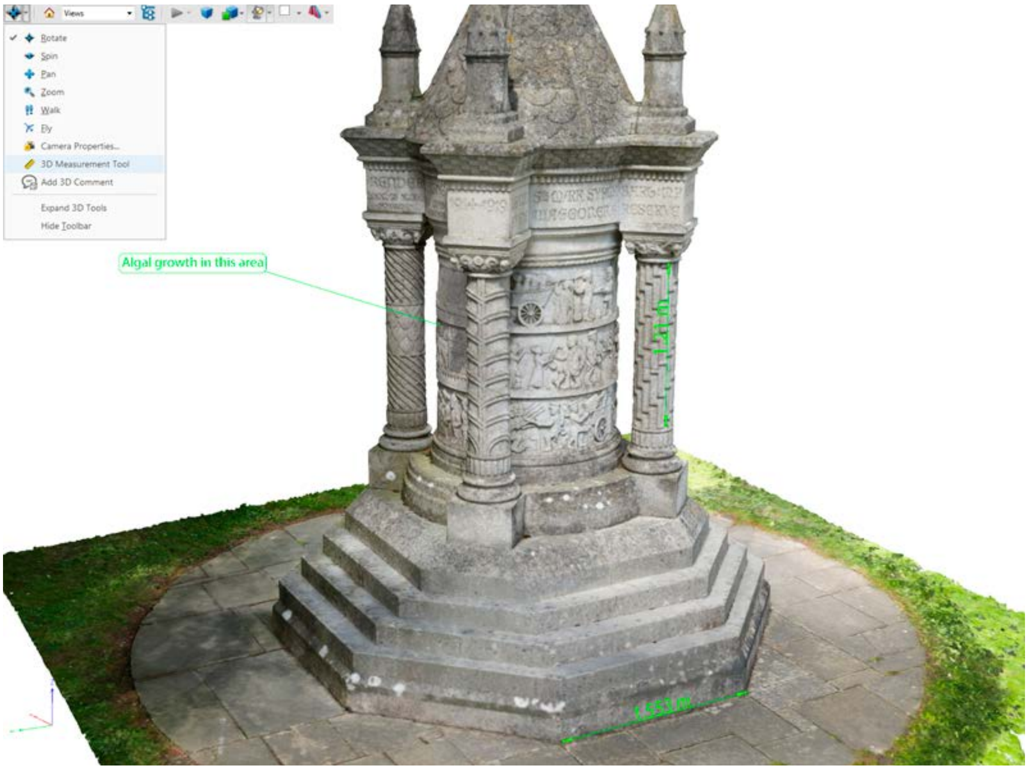


Figure 86
Annotation and measurement capabilities in a 3D PDF.

Online resources such as Sketchfab offer a useful service for sharing and viewing models both publicly and privately, and 3DHop provides another very useful open-source method of sharing even high resolution models on standard web pages. Other sites offer more comprehensive services, for example Drone Deploy, which both processes uploaded aerial imagery and can be used to disseminate the results.

Textured 3D models can be useful under some circumstances. They can provide 'virtual access' to areas that cannot normally be reached (Figure 87 shows the painted interior of Longhtorpe Tower, Cambridgeshire, to which disabled access is compromised), can be used for generating sections and profiles, and can be used as the basis for 3D-printed physical models.

3.6 3D printing

Once models of objects have been produced, there is the potential to produce 3D-printed replicas or scaled representations, for example for educational or display use. Such models need to be 'watertight', that is have no holes in them, and models derived from photogrammetry often require a considerable amount of editing to optimise the mesh and remove, for example, intersecting faces, non-manifold faces, small tunnels and connected components. In most objects with complex undercutting geometry there will be areas that could not be covered in the survey, and some interpolation will be necessary to provide a watertight model. There are many pieces of software available commercially that can provide this functionality,

Figure 87
Photogrammetric model used to enable 'virtual access'.

but there are also several free packages that will enable you to produce a watertight model, and check a model for its suitability for 3D printing. Netfabb is one example, and checking can also be carried out with the open-source Meshlab.

3.7 Community involvement

The ubiquity of cameras and the high quality of images that can be achieved using, in many circumstances, just the automatic settings, means that projects with community (non-professional) involvement are a distinct possibility. Early examples of this, employing older software but applying the same principles outlined here, include NADRAP, which was able to generate excellent and useful results. More information can be found on the Archaeology Data Service (ADS) website. There are many other, more contemporary, examples of community inclusion projects (for example McCarthy 2014 and the ACCORD project where photogrammetry has been used successfully. The availability of free software (see Software (page 17)) enables the production of 3D models and outputs that can be scaled and orientated later, provided that the scale bars and other necessary information have been included in the images.

Crowd sourcing can be a good way of collecting raw imagery but it is important to ensure that those providing the photography understand the sort of images required and that they must not have been cropped or had special effects applied. That said, some very impressive results have been obtained by using whatever was available for sites that have now been lost (for example the photogrammetric reconstruction of the Bamiyan Buddha statues (Grun *et al* 2004).When using whatever is currently available, be aware that people have a tendency to take (more or less) the same images or views of a subject, so complete coverage is typically not achievable, and you may not know whether arbitrary cropping and treatment of images with 'special effects' has taken place, which will heavily compromise their photogrammetric usefulness.

3.8 Metadata and archive

The ADS provides several useful guides regarding the metadata required for archiving archaeological projects and their constituent components on their website. These include close-range photogrammetry and *close-range photogrammetry* and *SUA survey*.

In some circumstances archiving the original images and control data captured on site may be sufficient: the analytical results are usually presented as part of the final report. If the 'raw data' are archived correctly, the reconstruction can always be processed at a later date, as was often done with, for example, ante-disaster stereo photogrammetric imagery in the past, and the user will often therefore be able to take advantage of subsequent developments in software and hardware. This represents a significant difference and potential advantage compared with most other types of data gathered on any site.

4 Case Studies

Case Study 1: Using archive aerial imagery

Comparing digital surface models created from archive aerial photography using SfM and stereo-matching photogrammetry software at Eggardon Hillfort, Dorset.

Introduction

Archive stereo-aerial photographs (SAPs) from 1948 and 1984 of Eggardon Hillfort and its landscape, near Bridport, Dorset, were processed using photogrammetric software to create digital surface models (DSMs). DSMs are useful for illustrative and analytical purposes in archaeology, and their production promises to be faster and cheaper with the advent of structure from motion (SfM) software in comparison with high-end alternatives.

However, SfM software is optimised for use with a large number of overlapping, converging images, which does not necessarily match the requirements for SAPs, which are a 60 per cent forward and a 20–30 per cent side overlap with parallel, or very slightly converging, geometry. As an example, Agisoft LLC (2014) illustrate ‘capture scenarios’ in their manual and suggest overlaps of +80 per cent forward and 60 per cent side, which is unlikely to be met by archived SAPs. This raises the question of how well SfM software can produce DSMs compared with outputs from high-end alternatives.

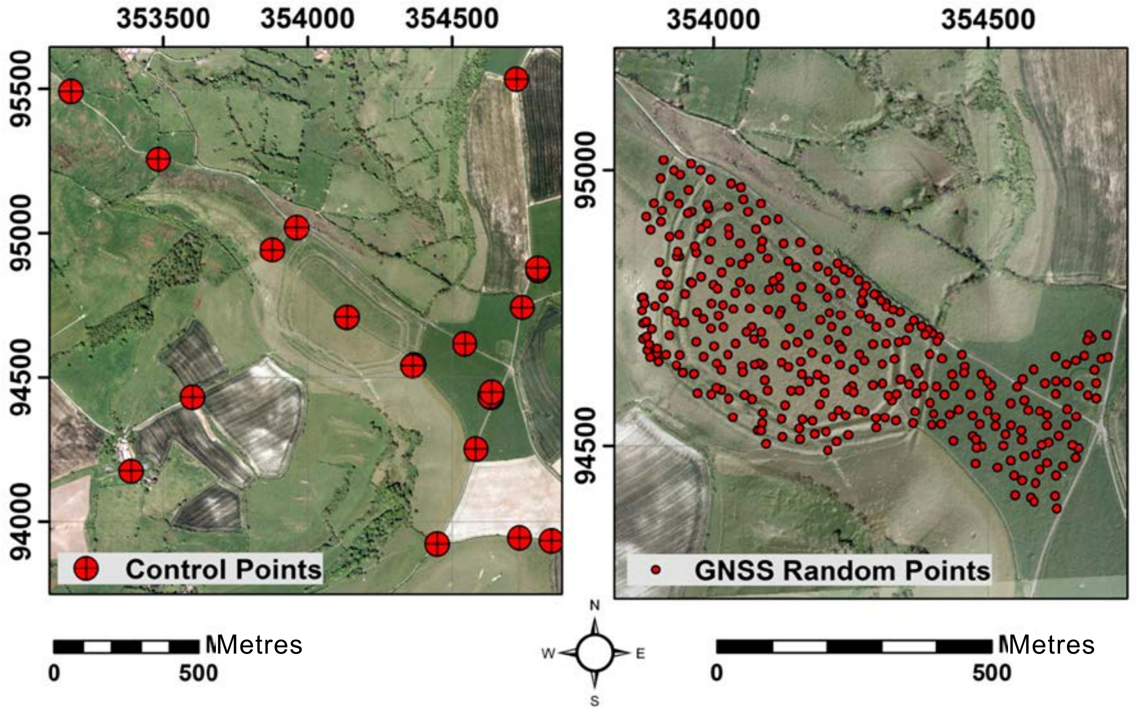


Figure CS1.1
The location of GCPs within the hillfort landscape.
© Heather Papworth

Software and methods

DSMs were created using SocetGXP, a high-end software package from BAE Systems, and PhotoScan SfM software, from AgiSoft. No camera calibration details were available for the SAPs, which were digitised from original negatives using a photogrammetric scanner held by the Historic England Archive in Swindon. Ground control points (GCPs) were collected using a Leica Viva global navigation satellite system (GNSS) (Figure CS1.1).

The processing workflows in each software package are significantly different to each other, although both require iterative processes of checking and re-checking the quality of the photo bundle block adjustment to obtain an optimal solution. This is gauged in both packages by examining residual errors for the ground control and check points, which are given in metres and pixels. To refine errors, further alterations can be made to loosen or constrain the accuracy of the camera, GCPs and check point locations, for example. The process of block bundle adjustment can then be repeated and the residual errors re-examined. After completing this process in PhotoScan and SocetGXP, the point cloud was exported for interpolation in ArcGIS 10.1, using the Natural Neighbour function, to produce a raster DSM with a 1m pixel resolution. The results are shown in Figure CS1.2.

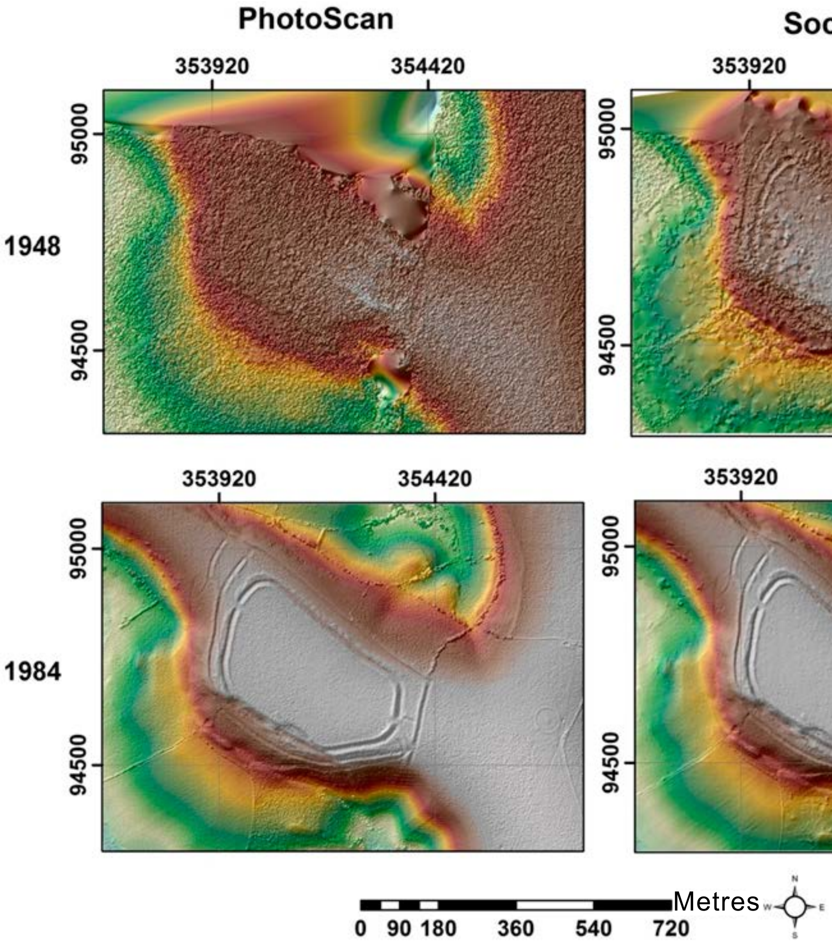


Figure CS1.2
DSMs generated from 1948 and 1984 aerial photography using PhotoScan (left) and SocetGXP (right).
© Heather Papworth

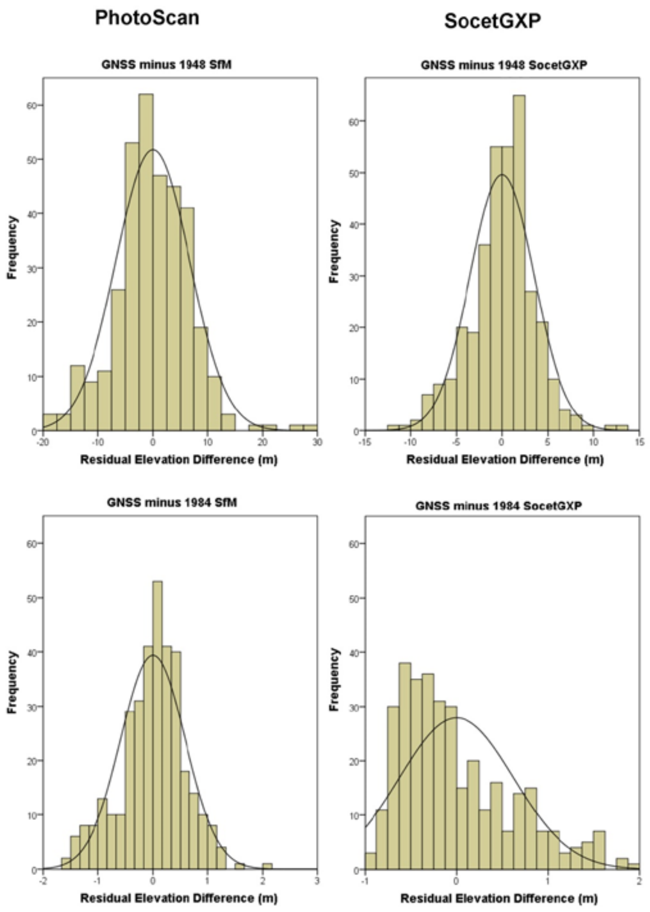


Figure CS1.3
Residual histograms showing the range and magnitude of elevation error when comparing the DSMs with GNSS elevation values.
© Heather Papworth

To assess the accuracy of elevation values in each DSM, an independent data set was created by using the Leica Viva differential GNSS to record a large number of elevation values across the hillfort at random locations with an uncertainly of less than 0.014m. These points were imported into ArcGIS 10.1 and used to extract coinciding elevation values from each DSM. Summary statistics comparing the GNSS elevations to those of each DSM were created using the statistical software SPSS.

Comparison of DSMs

A visual assessment of the DSMs (Figure CS1.2) produced by both PhotoScan and SocetGXP showed minimal differences between the 1984 results, although the PhotoScan DSM contained more details along the hedgerows. Despite the 1948 DSMs both containing excessive noise, the hillfort ramparts were visible in the SocetGXP dataset. This type of assessment may be sufficient if a DSM is intended for illustrative purposes, but data quality is an important consideration when analysis is to be undertaken, such as the construction of viewsheds or cost-path analysis.

Histograms illustrating the residual difference between the GNSS and DSM elevations (Figure CS1.3) were useful for visualising the range of residual errors (*x*-axis) and how often they occurred (*y*-axis). If errors within the data are random, the shape of the curve fitted to the graphs should be bell-shaped. If a bell curve is not apparent, this could indicate a systematic error present in the data, as shown by the bottom right-hand image in Figure CS1.3. A further issue highlighted in Figure CS1.3 was the larger range of errors contained within both of the PhotoScan DSMs compared with those generated using SocetGXP. This was confirmed by the range variable, shown in Table CS1.1, which could indicate that the PhotoScan DSMs were not as accurate as those from SocetGXP.

However, further analysis of the statistics contained within Table CS1.1, such as the standard deviation (SD), RMSE and confidence intervals, suggested that the 1984 PhotoScan DSM was slightly more accurate than the SocetGXP DSM: the residual values were all slightly smaller for the 1984 PhotoScan dataset. For example, the RMSE value comparing GNSS elevations with those from the 1984 PhotoScan DSM was 0.587m compared with 0.622m, the value returned from the same comparison with the 1984 SocetGXP DSM. The opposite was true for the 1948 DSM results: SocetGXP considerably out-performed PhotoScan. Overall, the results demonstrated how important it is not to rely on just one method for assessing data quality.

Conclusion

The results of this study demonstrate that stereo-matching photogrammetry software, namely SocetGXP, generates a more accurate DSM when processing older SAPs. However, DSMs produced from more modern SAPs using SfM software, particularly PhotoScan, are comparable with, if not slightly more accurate than, those created with specialist packages.

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Case Study 2: SUA imagery on single sites

Assessing the value of photogrammetrically processed imagery from SUA at Thornton Abbey and Ashnott lead mine.

Thornton Abbey

Thornton Abbey is the site of a major Augustinian house located in North Lincolnshire at national grid reference (NGR) TA11801895. Now chiefly known for the surviving remains of the large and ornate fortified gatehouse, it was the subject of historical, archaeological and architectural research undertaken by English Heritage between 2007 and 2010 (English Heritage 2010b). Part of this research involved a detailed archaeological survey of earthworks between the claustral buildings and the gatehouse (Figure CS2.1). The survey provided evidence of the medieval construction sequence, as well as garden landscaping associated with the construction of a stately home on the site in *circa* 1607 for Sir Vincent Skinner and the sites of a number of 19th- and 20th-century archaeological excavations. The entire precinct is designated as a scheduled monument (List entry Number 1011198), while the gatehouse and ruins of the claustral buildings have been in state guardianship since 1938. The existence of the archaeological survey was the main reason why the photogrammetric survey was undertaken: to benchmark the technique against an existing survey and to examine the correlation between the two, providing an estimation of the performance of the photogrammetric product and evaluating its potential contribution to the field-recording workflow. The area flown corresponded to the area that had been studied and presented in the 2010 report, and measured approximately 500×250m.

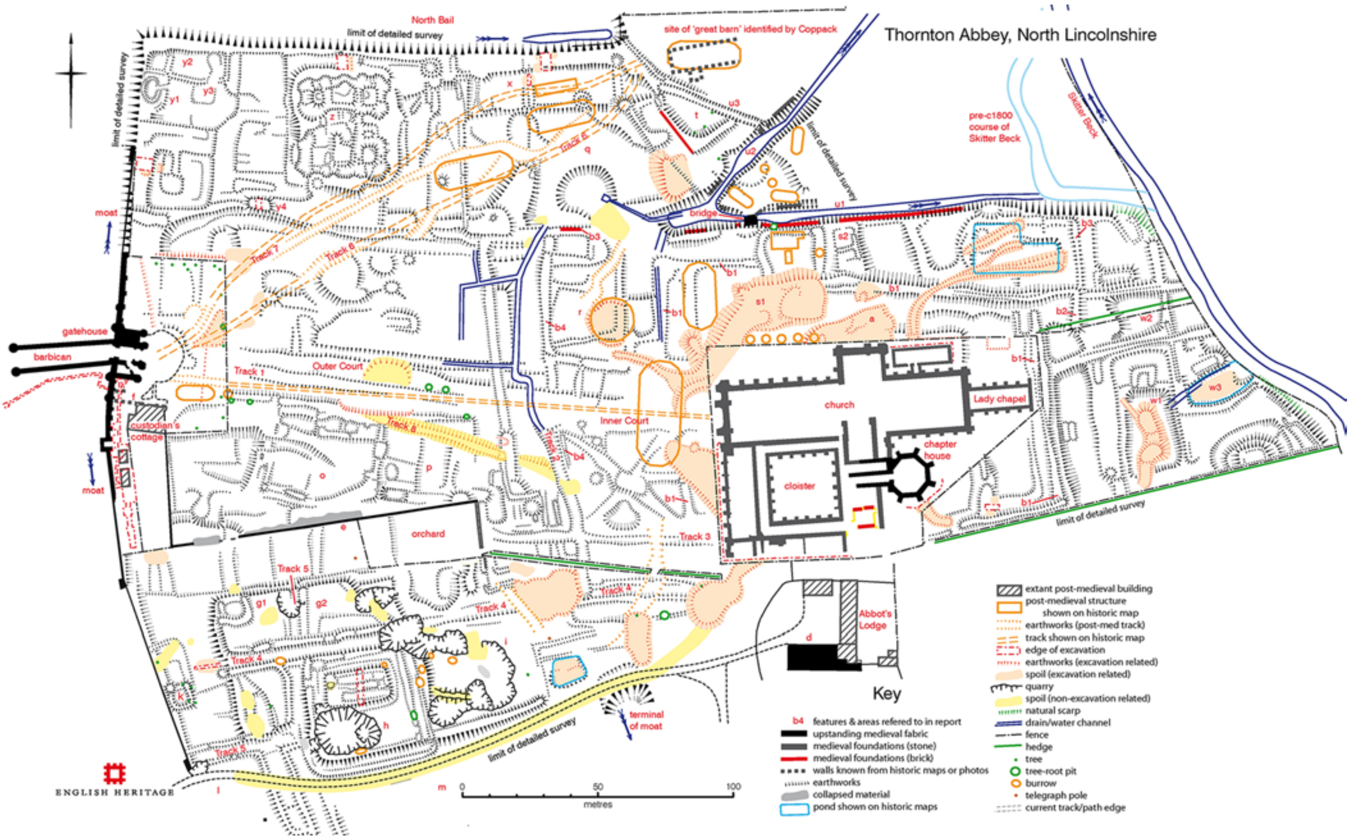
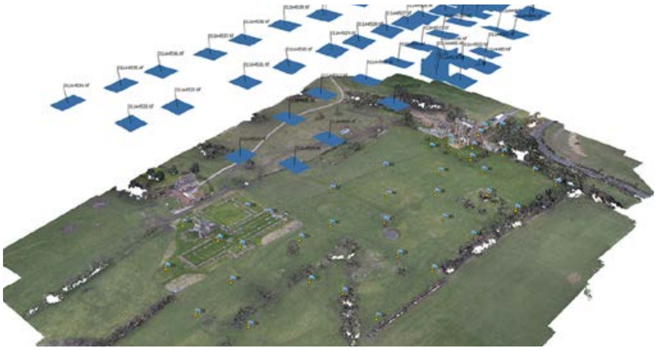


Figure CS2.1
Results of archaeological earthwork survey.

The site was flown using a subcontractor (Skyline Images Ltd) using a Droidworx XM8 octocopter, carrying a Canon EOS 5D mark III digital single lens reflex (DSLR) camera. Ground sample distance (GSD; the distance on the ground represented by a single pixel in the images) was specified at 40mm, which, with the lens used, dictated flying at the legal ceiling of 120m (as stated in Civil Aviation Authority regulations). The site was covered by 56 vertical or near vertical shots. The brief specified a front-to-back overlap of at least 80 per cent and a side lap between swaths of at least 60 per cent. A small number of oblique images was also included for processing. Immediately prior to image acquisition, a network of control points was established across the site. The ground control points (GCPs) themselves were paper plates pinned by survey pegs: these are cheap, clearly visible and unambiguous in the aerial photography and are easy to place and remove. The presence of livestock and the imminence of summer opening to the public precluded the use of paint marks, and the area of interest had no points of hard detail that were suitable as GCPs. The GCPs were used to optimise the alignment of the aerial images and to put the survey 'on the map' in the correct position and orientation. The imagery was processed using Agisoft Photoscan Pro. After structure from motion (SfM) alignment and filtering, half of the GCPs were added as control and for alignment optimisation, and a sparse point cloud of approximately 250,000 tie points was produced. The remainder of the GCPs served as check points. A dense point cloud was then generated. The camera positions can be seen above the point cloud in Figure CS2.2, and small flags denote the GCPs.

The dense point cloud was classified to remove trees, scrub and larger buildings such as the gatehouse and Abbot's Lodge farmhouse (Figure CS2.3). A mesh was generated using only those points classified as ground. The resulting digital elevation model (DEM) was exported for use in a geographical information system (GIS) for processing and analysis, along with a composite ortho-image derived from all the input images.

Analysis was conducted using ArcGIS, although the techniques employed were straightforward and could be replicated in many open-source alternatives. The DEM provided the basis for a composite hillshade (Figure CS2.4), which elucidated many of the ground variations hinted at in the raw DEM. Archaeological features were clearly visible between the gatehouse and claustral range. In addition, a slope analysis was used (Figure CS2.5); flatter areas are shown in green, intermediate slopes in yellows and steeper slopes in reds. Clearly, many other analytical processes could have been applied to the data. Both outputs demonstrated a very strong correlation with the hachured plan derived from the previous site survey (Figure CS2.6), which was the hoped-for result, and demonstrated that, in theory at least, the technique has potential for archaeological landscape investigations. Although the analyses were clearly not interpretative products they did show some features and areas that may benefit from further examination.



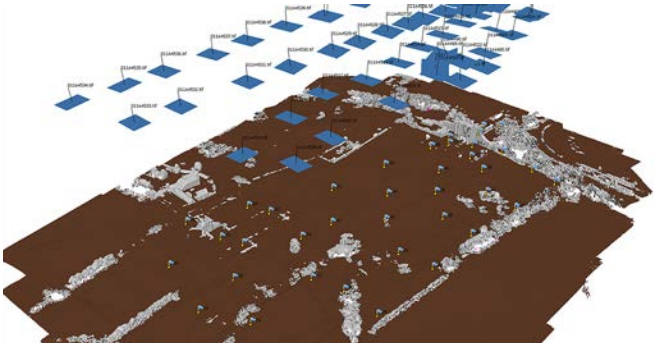
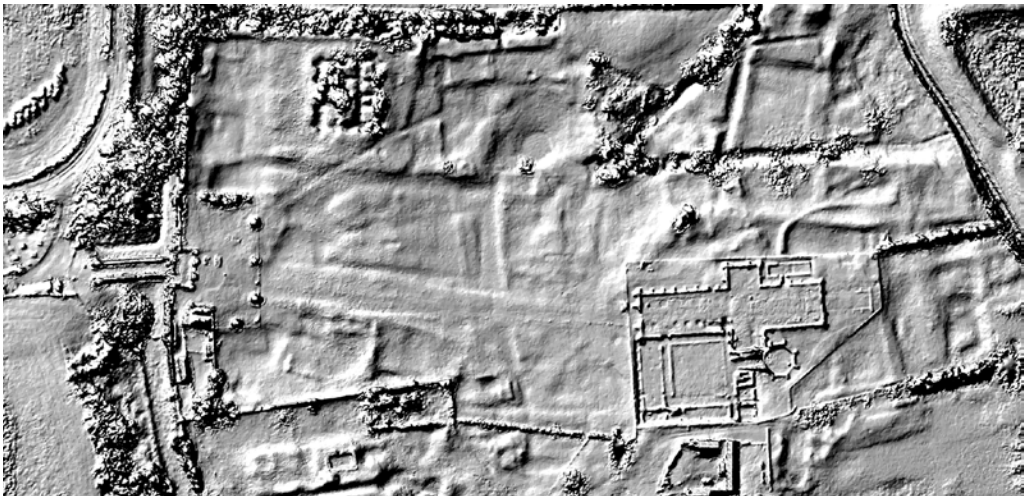


Figure CS2.2 (top)
The dense point cloud generated from the aerial photography.

Figure CS2.3 (bottom)
The classified point cloud, showing filtered buildings, trees, scrub and dwarf walls.



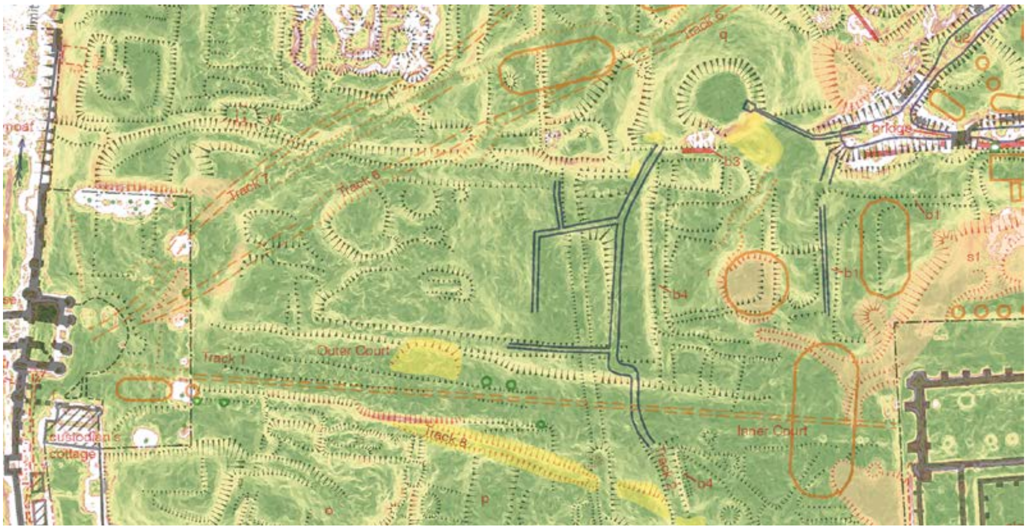


Figure CS2.4 (top)
A hillshade of the unfiltered digital elevation model.

Figure CS2.5 (middle)
Slope analysis of the digital elevation model.

Figure CS2.6 (bottom)
Extract of hachure plan overlaid on slope analysis, showing strong correlation between the two.

Ashnott lead mine

Based on the encouraging results from Thornton Abbey, it was decided to see whether the approach could be developed further to help the English Heritage Assessment Team with a new request for an analytical survey of a Heritage at Risk site at Ashnott in Lancashire. The scheduled remains of Ashnott lead mine lie on and within a small limestone knoll on the edge of the Hodder valley north of Clitheroe, in the southern part of the Forest of Bowland area of outstanding beauty (AONB). Documentary research has shown that the mine may have been active around 1300 and was certainly a going concern when Thomas Proctor entered into a 3-year lease with the Duchy of Lancaster to ‘digge, take & myne leade’ at ‘Asshe Notte’ in 1538. By the time the mine closed in the 1830s, the victim of a general slump in lead prices, generations of miners had created a tightly knit complex of surface workings and underground levels chasing the erratic patterns of mineralisation throughout the knoll. The survey was required to understand how this mine had developed and to ensure that new fences, intended to safeguard the remains by improving stock management, were correctly placed around the most significant parts of the site. It was also designed to highlight places where the collapse of old, poorly sealed shafts presented a danger to livestock and hill-walkers.

Figure CS2.7
Hillshade of unfiltered DEM of Ashnott Mine.

The site was flown in a similar fashion to Thornton Abbey, this time by Aerovision UK Ltd using a fixed-wing senseFly eBee small unmanned aircraft (SUA) carrying a Canon Ixus ‘point-and-shoot’ camera. Once again a network of highly visible markers was positioned across the target area to provide ground control. The imagery was processed as above, but in this case the digital models (for example Figure CS2.7) were used by the Assessment Team to draft, in AutoCAD, an outline plan of the earthworks similar to those normally created through earthwork survey, by marking lines along the tops and bottoms of slopes. This plan was then taken back into the field, where it was verified, refined and augmented by close observation and the judicious use of survey-grade global navigation satellite system (GNSS) equipment. The resulting earthwork plan, with slopes expressed with hachures in a readily readable form (Figure CS2.8), was somewhat less detailed than that normally produced by traditional ground-based survey. It was metrically accurate, however, and sufficiently nuanced to support the archaeological analysis of the site as described in the accompanying survey report. Crucially, this approach was perfectly adequate to identify the concerns that had led to the site’s inclusion on the Heritage at Risk Register and to provide the details required to guide conservation measures in a forthcoming Higher Level Stewardship agreement. Measured against the scale of survey standards published by English Heritage, in which Level 2 records the general form of a monument and Level 3 captures its complexity, this SfM-derived method sits at about 2.5 or perhaps a little higher. It certainly suited the requirements at Ashnott and, in terms of the fieldwork, took less than half the time required for a comparable level of detailed field survey. However, while detailed and highly flexible three-dimensional (3D) imagery is a tremendous tool, interpretations derived from it must still

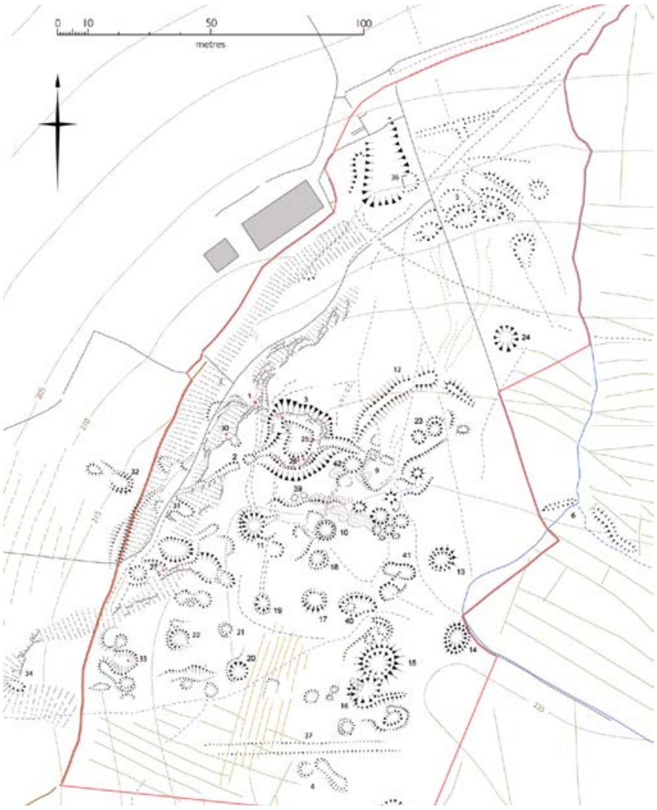


Figure CS2.8
Extract from the earthwork interpretation plan for Ashnott, derived from the DTM and ground observation.

be informed by an experienced eye if they are to be robust. From the surveyor's perspective, the most valuable parts of the process were the site visit before the flight, which provided a good understanding of the site prior to mapping the patterns observed from the air, and the detailed reassessment of the SfM-derived plan when it was taken back to the site. Only then did the finer distinctions between paths and watercourses, washing floors and working areas, become fully apparent.

Case Study 3: SUA landscape survey

The 2015 Rievaulx Abbey landscape survey, North Yorkshire.

Introduction

Rievaulx Abbey is located on the southern fringes of the North York Moors in the Rye valley, 4 miles upstream and west of the historic market town of Helmsley, North Yorkshire). The abbey buildings occupy a naturally elevated terrace to the eastern side of a steep-sided wooded valley. The valley floor is predominantly flat and under pasture, housing the village of Rievaulx. The abbey remains and their immediate surroundings are in the care of English Heritage, while the rest of the valley is privately owned.

The most comprehensive survey of the abbey's landscape has been Caroline Atkins' 1996 investigation, which formed part of Fergusson and Harrison's study of the site (Fergusson and Harrison 1999). English Heritage's 2001 conservation plan identified the need for a full programme of landscape survey and analysis of the site (English Heritage 2001, 64). In 2005 English Heritage undertook a study of the abbey and its landscape (Dunn and Pearson 2005). At that time it was not possible to undertake a detailed survey, so Atkins' 1996 survey was utilised for the 2005 study; the published survey report (Dunn and Pearson 2005) then represented the most up-to-date interpretation of Rievaulx's landscape. As this survey is now more than 20 years old, the site has recently been re-surveyed using modern techniques.

Methodology

The survey was conducted using a structure from motion (SfM) and multi-view stereo (MVS) approach, using low-level aerial photographs. The Rievaulx landscape provided the opportunity to test this methodology against traditional survey techniques and Environment Agency (EA) 0.5m^2 lidar data. A *circa* 48ha survey area was identified, which encompassed the abbey remains, the village and surrounding farmland. Historic England commissioned an external contractor to overfly the area using a small unmanned aircraft (SUA). This captured overlapping vertical photographs from an altitude of *circa* 180m,

Figure CS3.1
Hachure plan derived from the new survey.

80m above the valley floor. To facilitate georeferencing, ground control points (GCP) were installed across the valley using a survey-grade global navigation satellite system (GNSS), employing markers identifiable in the images.

The SUA was equipped with a Sony Alpha ILCE-A6000, a 24.3MP digital camera, triggered by the SUA on-board software. The automation facilitated a pre-determined ground sample distance (GSD) and level of image overlap of 0.05m and 80 per cent, respectively. To ensure total coverage, two flights were undertaken with identical flight plans, although the actual paths differed slightly because of localised weather conditions. Six hundred and six images were captured. Each image was manually quality checked to ensure only clear images were processed; 42 images were removed from the data set because of their poor quality. The camera operated in shutter priority mode, ensuring a fast shutter speed was maintained, improving the chances of capturing clear images; a speed of 1/800th of a second and an ISO of 800 were used. The f/stop varied between f/2.8 and f/5.6 to compensate for the variable lighting conditions; Figure CS3.2 shows an example image.

Images were processed using Agisoft Photoscan Professional. The SUA on-board software logged the camera's position and orientation during each image capture. This combined with the images was uploaded for processing. Initial image alignment used the SUA log, and then this was refined using the GCPs, which were manually identified in each image. Using the SUA log considerably decreased the processing time for the initial image alignment. The SfM approach created a continuous ortho-image, then a DSM was generated using the MVS process. The DSM was accurate to *circa* 20mm in the horizontal and *circa* 35mm in the vertical plane. This accuracy was measured using check points that were GCP that had not been used for refinement. Once generated, the DSM was manipulated in a geographical information system (GIS) to assist the identification and interpretation of topographical features.

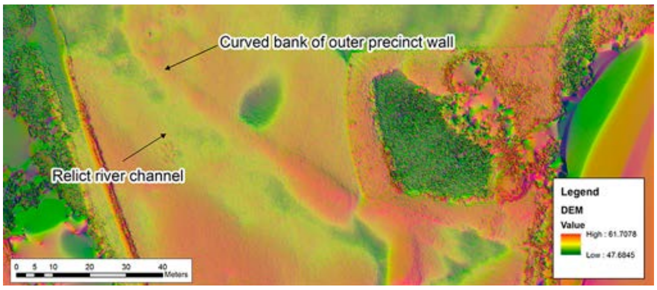
Results

Following the GIS manipulation, a range of features was identified. In some cases the survey enhanced existing knowledge, and in others it identified previously unknown features. These features were visualised as a hachure plan (Figure CS3.1) to allow direct comparison with the 1996 survey. An example of this enhancement could be seen when the southern precinct wall was examined. The SUA data showed this as a low bank, curving as it crossed the valley; it was apparent that this curve followed that of a relict river channel (Figure CS3.3). The channel may have been visible as a shallow boggy depression when the precinct wall was constructed and offers an explanation for the curving bank; the monks may have chosen to enhance the precinct wall using this natural feature. This relationship had not been previously identified and without the SUA methodology it would have remained unnoticed.

Figure CS3.2
Example of the imagery captured using the SUA.

Evaluation

This case study highlights the nature of survey available via the SUA methodology. It is high resolution and highly accurate, although there were significant areas where no data could be obtained because of vegetation coverage. A lidar approach delivers greater coverage at a lower resolution, which can be seen in the comparison of the methodologies illustrated in Figure CS3.4. Nonetheless, these methodologies should be viewed not as competing but as complementary. Ideally SUA data should be obtained for open areas and lidar data for wooded regions, thus optimising coverage and resolution. The SUA approach allowed data to be collected from a large area quickly; the initial data collection was achieved in half a day and the subsequent ground-truthing in one day. An alternative methodology is ground-based survey, but for this scale of survey a team would need to be deployed for an extended period of time to collect the requisite data, and it is questionable whether the same resolution could be achieved.



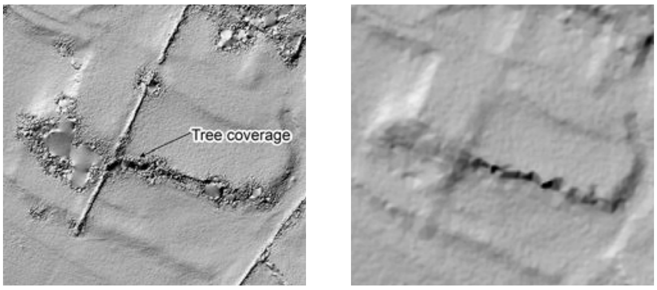


Figure CS3.3 (top)
Hillshaded view of the southern outer precinct wall showing the curving bank following the line of the relict river channel to its south.

Figure CS3.4 (bottom)
Comparison between SUA (left) and EA lidar (right) imagery.

Not all locations are suitable for the SUA methodology; areas with significant tree cover will not be productive. Locations with adverse weather conditions are not ideal for SUA either. Even at Rievaulx, in a relatively amenable location, poor weather caused the survey to be rescheduled on three occasions. However, the SUA approach drastically reduced the fieldwork required, as the majority of the work was desk-based. This reduced staffing costs compared with traditional methodologies, although the data-capture and processing costs do need to be taken into consideration. Nonetheless, compared with ground-based survey, the SUA methodology can deliver savings and should be considered at suitable locations. The resulting plan has added detail to the 1996 survey and thus shed new light on the Rievaulx landscape. This survey will ultimately help inform continued management of this significant site and help protect it for the future.

Case Study 4: Combining SUA and terrestrial data

Tintagel Castle, Cornwall.

Introduction

In late 2014, work was undertaken by Historic England on behalf of English Heritage to produce data for use in a new exhibition at Tintagel Castle, on the north coast of Cornwall. The brief included the production of a model of the site suitable for three-dimensional (3D) printing and other potential uses, including archaeological analysis and illustration.

The area to be surveyed comprised *circa* 2.5km^2 of highly variable terrain, including the castle and associated structures, two tunnels (one natural and one artificial), sea cliffs, and several other areas inaccessible from the ground. The accuracy requirements for the project involved the production of the 3D data with a ground sample distance (GSD) of approximately 40mm. In order to achieve this, photogrammetric survey from an aerial platform was the obvious choice for those parts of the island visible from the air, while terrestrial 3D laser scanning was used to record the tunnels, which could not be surveyed from the air.

Historic England subcontracted the acquisition of the aerial imagery to Future Aerial Innovations. Given the nature of the terrain, it was decided that the most efficient coverage would be obtained using a combination of fixed-wing and multi-rotor platforms to capture both vertical and oblique imagery. While the vertical imagery from a fixed-wing platform is perfect for larger 2.5D terrain models, this project required the cliff faces and castle ruins to be as detailed as the rest of the terrain to create a full 3D model. The fixed-wing platform, using a camera taking vertical imagery, was used for efficient coverage of the upper surface of the site, while the multi-rotor system was used for the cliffs and other vertical elements, such as the walls of the structures on the site. The fixed-wing solution could be flown on a pre-planned flight path, while the multi-rotor was flown manually. Although the entire site could theoretically have been captured using a multi-rotor small unmanned aircraft (SUA), the use of a fixed-wing SUA represented considerable time savings given the area to be surveyed.

Constraints

The subcontracted aerial work, given project deadlines, had to be flown in November and December of 2014. The location of Tintagel is such that, at that time of the year, there are strong prevailing winds blowing in from the Atlantic, lighting is challenging, and weather conditions are very variable. This meant that the multi-rotor SUA (an Ascending Technologies Falcon 8 equipped with a Sony A7R camera), which can be flown in windier conditions, was used until weather windows appeared when the fixed-wing SUA (a senseFly eBee, equipped with a Canon Powershot S110) could be deployed. Capturing the entire data set took several visits to the site.

There were also constraints on the terrestrial scanning. Merlin's Cave is tidal, so only relatively short windows of opportunity were available for the survey work there.

Flight operations

The camera on the multi-rotor was equipped with a 35mm prime lens. While the multi-rotor was capable of waypoint-driven flying, on the mainland valley area it proved to be more effective to fly it in manual mode, to give the camera operator time to frame images correctly. When flying in manual mode, extra care has to be taken to ensure that sufficient overlap is present.

Flying in waypoint mode proved to be more effective when capturing the oblique imagery of the island. The flight plan set the SUA 100m out to sea, at a height level with the top of the island and looking back towards the island, always focusing on a central point. A distance of 100m ensured the island was fully framed in one shot while maintaining the necessary 40mm GSD. To keep the SUA in sight and within 500m, both camera operator and pilot followed its path around the island on foot.

Considerable testing was required to get the correct flight height, shutter speeds and distances, especially in the tough weather conditions. Once fully set up, a total of 15 flights was required to complete the oblique phase of image capture.

A follow-up visit during more favourable weather was needed to capture the fixed-wing imagery, which proved to be a relatively simple task using the waypoint-driven capabilities of the SUA. Four flights were required to provide vertical imagery in two directions to ensure maximum coverage and overlap (Figure CS4.1). The standard camera was swapped for the upgraded Canon Powershot S110 with shutter priority mode. Given the prevailing conditions, without this the images would have been blurred.

Accurate ground control is essential in a project with so much topographic variation. A total of 25 ground control points (GCPs) was used (Figure CS4.2). Removable markers were specified, so that no trace would be left once the survey was completed. Because of the steep cliffs and rugged ground, putting in the ground control took a full day. The position of each point was surveyed using a survey-grade global navigation satellite system (GNSS) to an accuracy of approximately 10mm in *x*, *y* and *z*.

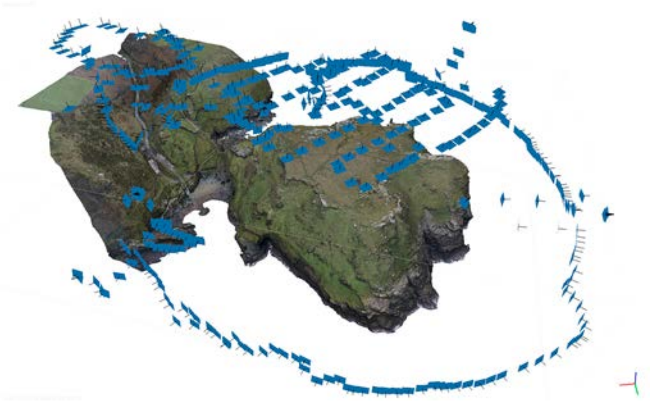


Figure CS4.1 (top)
Arrangement of the images used.

Figure CS4.2 (above)
Ground control points (in yellow) used for the survey.

Laser scanning

Terrestrial laser scanning was undertaken in two areas that could not be covered by the SUA imagery. These comprised the artificial tunnel on the top of the island, the use of which remains open to interpretation, and the natural

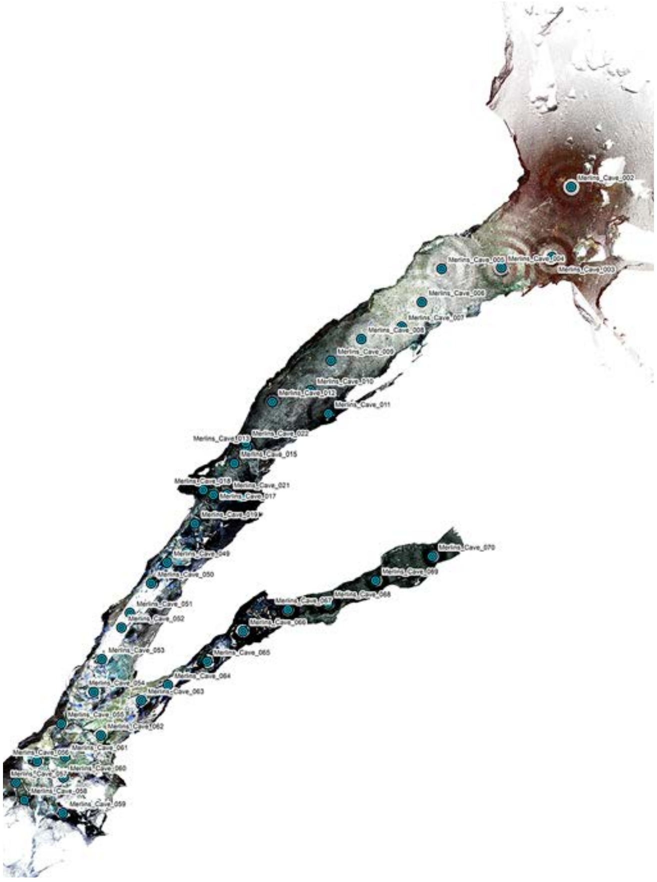


Figure CS4.3
Scanner setups for surveying Merlin's Cave.

Merlin's Cave. For both areas, a Faro Focus 3D laser scanner was used. The main consideration was portability. The tidal Merlin's cave required the survey be undertaken quickly, and the very variable conditions underfoot meant that a light instrument could only be used safely with two operators, keeping a watchful eye on the tides at all times. The laser scanning was also controlled by survey-grade GNSS, ensuring that the data could be integrated with that generated by the aerial photogrammetry.

Processing

The terrestrial laser scanning was undertaken and processed by the Geospatial Imaging Team at Historic England using Faro Scene. The number of scanner setups and control is shown in Figure CS4.3.

Processing of the aerial data was also undertaken by Historic England. A total of 662 images, both oblique and vertical, was supplied in RAW and TIFF formats along with the GCP positions and coordinate schedule. With the GNSS GCPs added, the data processed to an overall positional accuracy of 0.02m in *x*, 0.04m in *y* and 0.03m in *z* (RMSE). Data processing was undertaken using Agisoft Photoscan.

Figure CS4.4
Noisy inputs from a point-and-shoot camera.

Figure CS4.5
Cleaner images from a better camera.

Some issues became apparent at a fairly early stage of processing the vertical imagery. Given the payload constraints of a fixed-wing solution, only a relatively compact camera could be used. Because of the prevailing weather conditions, with high winds on overcast days, the camera was liable to increase the International Standard Organisation (ISO) values dramatically in order to obtain well-exposed images, given the high shutter speeds necessary to avoid motion blur. This had the knock-on effect of introducing considerable noise into the imagery (Figure CS4.4). Using noisy inputs meant that the model lacked clarity in some areas, and Historic England requested some areas to be re-flown with the multi-rotor equipped with a much better camera to achieve sharper images. When these images were received the difference in quality was considerable (Figure CS4.5).

Unfortunately, scaffolding had been erected in the intervening period between flights, so only the noisier imagery could be used for the digital reconstruction of the buildings housing the site's tea rooms (Figure CS4.6). Despite Figure CS4.6 showing a draft model processed at relatively low resolution to illustrate the problem, the difference in reconstruction quality between the two areas is striking, and clearly demonstrates the issues associated with the use of high ISO values on cheaper cameras with smaller sensors. The higher resolution imagery also helped considerably with the definition of archaeological features such as low walls, which were formerly more difficult to distinguish from the thick tufts of grass surrounding them.

Other issues were also generated by using imagery captured at different times. One of the products was a low-resolution textured 3D digital model to be used by graphic artists subcontracted to English Heritage to help with reconstruction drawings. As the original image set had been captured at low tide and the second set at high tide, considerable masking of images had to be done to ensure that the final texture represented the low-tide ground surface accurately (Figure CS4.7).

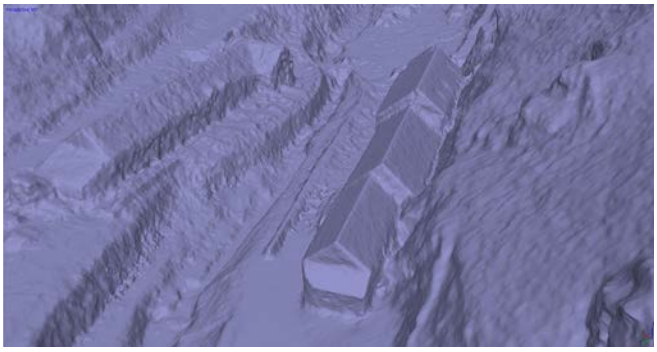


Figure CS4.6
Noisy inputs for the range of buildings on the left resulted in noisy data in that area of the model.

The terrestrial laser scanner and the photogrammetric data were combined and edited in Geomagic Wrap. This also involved conditioning the data so that is was suitable for submission to the 3D printing company, such as removing the self-intersections, small holes and small tunnels that are often produced during the meshing process and ensuring that a clean, 'watertight' mesh could be produced. The model was then re-imported into Photoscan for texturing and final export at a variety of resolutions.

Products

Given the necessary outputs for 3D printing and reconstruction drawings, the highest resolution model generated for the whole area comprised 42 million polygons, although, after trying the model at a number of different resolutions and texture sizes, the final one used for printing comprised approximately 15 million polygons. This was then used to construct the display model, originally routered from hardened foam. The net result was an accurate scaled model of the island and a section of the adjoining mainland (Figure CS4.8). The model used by the reconstruction artist comprised approximately 2 million polygons, as with a high-quality texture this retained enough geometric detail for its purpose.

Figure CS4.7
Texturing problems resulting from flights at different times.

Figure CS4.8
The model of the island in the visitors' centre.
© English Heritage

The printed model now forms part of a display in the new visitors' centre at Tintagel, with an overhead projection system overlaying the model with video showing the development of settlement and use of the island, in conjunction with an audio soundscape. The reconstruction drawings, based in part on the model, also form part of the exhibition (Figure CS4.9).

Figure CS4.9
One of the reconstruction drawings, depicting Tintagel in the Dark Ages.
Image by Monumental © English Heritage

Case Study 5: Terrestrial imaging on archaeological sites

One of the principal objectives of all archaeological recording is to create a record that is sensitive to post-excavation examination and re-interpretation. It is this requirement that makes the use of photogrammetry so revolutionary, as accurately created three-dimensional (3D) models, at appropriate resolutions, allow excavation data to be re-visited in a way not otherwise possible. Some enthusiastic promoters of the method argue, falsely, that it can be used to 'preserve heritage': an absurd assertion. What it can do, however, is accurately map a 3D surface and drape high-resolution photographic textures on that surface in such a way as to facilitate interaction and close examination that may not even be possible in the field. Three examples are presented here of the application of photogrammetric methods to archaeological excavation.

Roulston Scar, North Yorkshire

During the winter of 2013–14 an excavation was carried out to examine the defensive rampart and ditch on the inland side of the promontory fort at Roulston Scar in the North York Moors National Park, North Yorkshire. The excavation was undertaken to try and recover dating and environmental evidence and learn more about the scale of the defences on the eastern side of the hillfort, where they run along the steep side of the promontory. The excavation was undertaken to document a single section through the rampart and ditch. It was intended to be a 2-week project but it was quickly realised that the scale of the monument was such that this would be impossible. The trench was located at the point where the natural topography of the hill created a very small ditch cut into the natural slope that would have served as an effective defence. However, the ditch in fact measured 6m wide and over 2m deep, cut into bedrock, and was too deep to excavate in the original 2m wide trench and had to be extended to maintain safe working conditions. The prevailing weather conditions were also poor, so it was decided at the outset to record the plan and sections using photogrammetry for the primary record, backed up with interpretive drawings. The objective to record each deposit individually prior to removal, to allow for later re-assembly in the archive, was in this case impractical; the ditch was so large that the section had to be extended largely by machine to comply with health and safety requirements.

The primary trench was only 1.8m wide, so targets to provide a sufficient density of accurate points for georeferencing the 3D model were fixed at 1m intervals on the surface just beyond the edges of the trench. Additional targets were installed in the base of the trench and in the sections; these were required to give a more 3D georeferencing point network that covered the trench both in plan and from a sectional point of view (Figure CS5.1). Although a single network of points placed around the edges of the trench would doubtless have supported the production of a high precision plan or ortho-image, to maintain the same precision vertically within the trench other points were necessary along the base and sides of the trench. The targets were printed on high-density matt plastic, with industrial-grade hook-and-loop tape mounted on the back and firmly attached to perforated mounts nailed in place with 100–150mm nails. This approach is flexible, the targets are washable and reusable, and it is easy to position them even when ground conditions make it difficult to find a secure mounting point at first attempt. To ensure accuracy, where targets

Figure CS5.1
A completed 3D model showing the excavated section through the rampart and ditch at Roulston Scar, viewed in Sketchfab. Note the positions of the georeferencing markers around and inside the trench.
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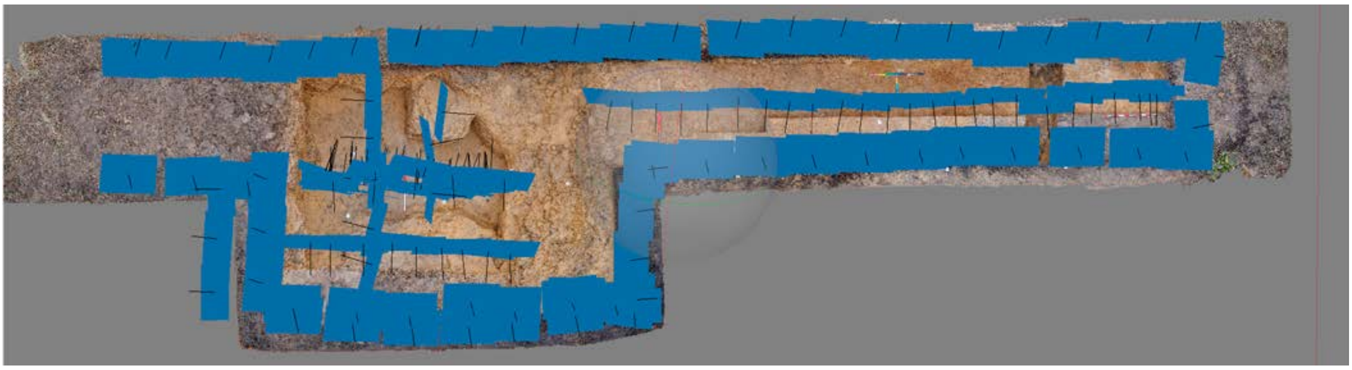
are not firmly attached to static structures, they should be re-surveyed each time a new model is generated.

It is essential that every part of the subject to be modelled is covered by a minimum of three overlapping images, ideally from a position that is at a right angle to the area to be modelled. This requires careful observation in environments where stone structures, etc, have considerable depth.

Figure CS5.2 shows a screen-shot in Agisoft Photoscan Pro of a model of the primary trench through the defences at Roulston Scar, with the camera positions marked in blue. A photo mast was set at an elevation of about 4m, and two strips of images recorded along each side of the trench. A third strip was taken using a tripod within the trench to record the section, in each case the camera was moved at approximately 1m intervals. The ditch was recorded using extra high-level pole photographs and further runs of



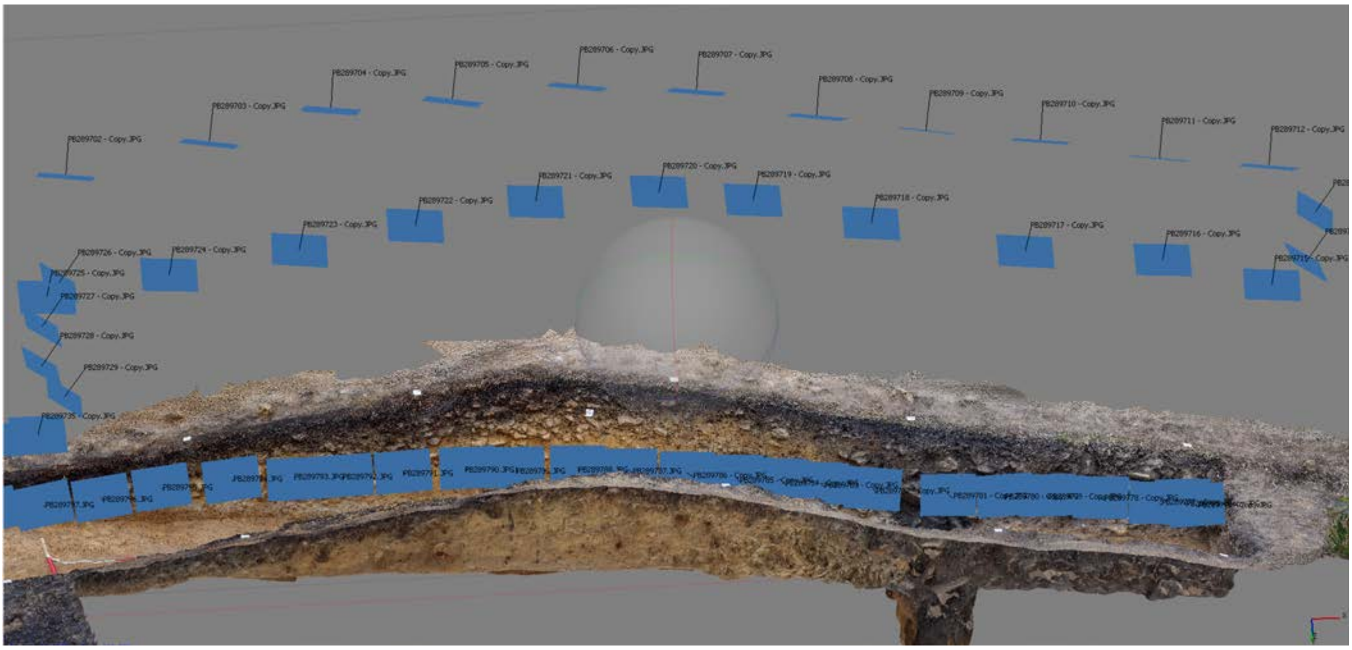


Figure CS5.2 (top)
A screen-shot from Agisoft Photoscan Pro showing a vertical view of the excavation trench with camera positions in blue.
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Figure CS5.3 (bottom)
A screen-shot covering an oblique view of the north-facing section through the hillfort rampart showing camera positions for recording plan and section.
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images facing each section. Figure CS5.3 shows an oblique view of the excavated trench through the modelled rampart at Roulston Scar, showing the camera positions used to provide coverage for a complete model reconstruction, ensuring that detail can be viewed in plan and in section.

It is important when working in the UK to appreciate that when georeferencing using national grid coordinates recorded to millimetre precision, as generated when saved from the survey instrument, the values are too large to be properly handled within most 3D computing environments, which rely upon the use of Open GL software. To avoid such problems coordinates should be reduced to exclude the 100km and 10km values at the beginning of each easting or northing value, respectively. If by unfortunate accident you happen to encounter coordinates that cross the 10km or 100km boundaries, a site grid should be used with an identified offset to reduce the number of digits in each axis. Any such shift should be documented and recorded as part of a log file describing the processes and software used, and added to the archive.

Once a model has been created in the field, it should be checked for completeness, scale and accuracy and checked against the physical evidence to underpin the overall recording process. Publication, giving live access to the 3D models, can be achieved using Sketchfab and other online tools; the data can be archived as an object model with its texture files as well as in Adobe 3D PDF format. Agisoft Photoscan Pro and many other software packages can be used to create 3D PDF files; experimentation using different software has shown that the output from the same 3D model is not always the same, but in the long term this is not critical if the source files are archived with the PDF and the export software used is recorded. 3D PDF files are internationally accepted as a recognised archive format and, if correctly scaled, give the user unprecedented access to the model in ways that can help support future research. Figures CS5.4 and CS5.5 are screen-shots showing the Roulston Scar rampart section annotated with observed notes and measurements.

Figure CS5.4 (top)
Completed 3D model incorporating an annotation and archived as a 3D PDF file.

Figure CS5.5 (middle)
A view of the completed 3D model of the excavated rampart section, published as a scaled model in PDF format suitable for accurate measurement purposes.

Figure CS5.6 (bottom)
Excavation photograph showing a late palisade trench cut behind the rampart of the prehistoric hillfort. The stratigraphy suggests that the palisade post-dates the fully eroded rampart and could relate to the Battle of Byland in 1322.
© Dominic Powlesland

The Roulston Scar excavation was inspired by a need to assess the date of this monument and secure environmental evidence that would allow it to be placed in the wider environmental context emerging from the examination of peat and pollen evidence recovered from the very much smaller hillfort at Boltby Scar. The use of photogrammetry produced a far higher quality record than would otherwise have been possible, given very tight time constraints and poor winter weather. In this case the very limited amount of time meant it was not possible to process the models and examine them on site before the trench was backfilled. Careful examination of the 3D models after the excavation was complete revealed many details not observed in the field and a further small excavation was undertaken in January/February 2015 to try and resolve the questions arising from the investigation of the model and the need to secure dating evidence for what appeared to be a very much later palisade trench behind the rampart (Figure CS5.6).

The advantage of correctly georeferenced 3D models is clear when the 3D models from the two excavations at Roulston Scar are combined. The models were loaded together and the trench edges manually clipped where the two excavations intersected (Figure CS5.7).

Another benefit of using 3D models compiled using photogrammetry, which may not at first be apparent or even intuitive, is that when viewed on screen with an object viewer such as Sketchfab or using Agisoft Photoscan there are perceptible differences between the front and back. Logic suggests that this should not be the case, as the photographic texture draped on the model is the same; but while the applied texture is the same, the surface upon which the texture is draped is different when viewed from either side. The process of trowelling the surface, whether in plan or section, even when carried out to the highest standard, leaves trowelling artefacts such as smearing of the soils; in particular, where stones become dislodged from the sections they expose parts of the section that have not been smeared and, when viewed from the reverse side of the

Figure CS5.7 (top)
3D models from two trenches excavated in 2013/2014 and 2015 combined using the georeferenced data.

Figure CS5.8 (middle)
The south-facing trench section seen from the inside and outside. This image from a screen dumps lacks the acuity when viewed in 3D.

Figure CS5.9 (bottom)
Detail of a section viewed from ground-level showing a hearth, part of which is buried by collapsed rampart material. Without using a 3D model, this view could only be seen by placing your head on the ground surface, which is practically impossible.
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Figure CS5.10 (top)
Cook's Quarry, North Yorkshire. A 3D model produced from images captured using a SUA to map ancient wheel ruts before drying of the sands made them almost invisible.

Figure CS5.11 (bottom)
An enhanced version of the ortho-image shown in Figure CS5.10 to increase the visibility of individual wheel ruts and underlying features.
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section in a model, they have greater presence as the holes are inverted and therefore project towards the viewer (Figure CS5.8).

When viewed by eye, the section in the side of a trench can only be viewed conveniently from certain positions; using a 3D model, the viewpoint can be set at any position, making it possible to view details otherwise effectively impossible to see. Figure CS5.9 shows where burnt soils related to a hearth behind the rampart at Roulston Scar are clearly buried by collapse from the rampart.

Cook's Quarry, North Yorkshire

Some archaeological sites are so fragile or have features of such poor or very short-lived visibility that they cannot be conventionally recorded without, for instance, constant wetting of the soil to maintain feature visibility; something this is not always practical. At Cook's Quarry, West Heslerton, excavations undertaken ahead of sand extraction have been in progress over many years. The sandy soils and blown sands that are characteristic of this multi-period site dry out almost as soon as exposed, minimising the visibility of a large percentage of the exposed archaeological features. In response to the ground conditions, excavation tends to be conducted in small sections that progressively cover larger areas. For much of the excavation this approach is effective, but in some areas this makes it impossible to see extensive areas at any one time.

Excavations in the 1980s identified a set of features originally interpreted as plough marks but later shown to be wheel-ruts in a hollow way that was progressively filling with blown sand as the features were formed. The slight trace of the wheel ruts bounded by slightly denser sands and slight iron-panning rapidly dried out. By using a small unmanned aircraft (SUA) flown with a digital camera, we were able to create scaled ortho-image covering large segments of the track-way as they were exposed and cleaned, which will ultimately be combined to form the basis of an accurate plan. Because the textures used to show surface detail on the 3D model are derived from digital photographs, they can also be enhanced using conventional image processing techniques to increase contrast or change the colour balance to help isolate or emphasise detail. Image enhancement can be applied prior to texturing the model or to the ortho-image output from a model (Figures CS5.10 and CS5.11).

Star Carr, North Yorkshire

The fragility of some archaeological deposits is such that they decay on exposure, and when exposed over large areas are difficult or impossible to model using standard procedures. Excavations of waterlogged deposits are one such example: the anaerobic conditions prevalent in waterlogged peat mean that organic materials such as timber survive, in a way not encountered on dry-land sites, but as soon as these materials are exposed to the air they start to decay and distort rapidly. Although timber, for instance, can be very well 'preserved', it does not necessarily survive intact and unchanged; damage or decay of parts of the internal structure combined with pressures arising from the burial environment can reduce buried tree trunks to squashed objects that look like smoothed planks. Excavations of waterlogged sites in peat are particularly challenging, not only because excavated material decays and potentially distorts as it dries out, but also because the peat matrix within which the material is often found experiences deflection when someone stands upon or walks across it; this can affect the model-building process as the very material being modelled can move as it is recorded, and thus cause the resultant model to be imprecise with fuzzy boundaries. This is the perfect environment in which to use an SUV for image capture. An SUV was flown as low as a metre above the Early Mesolithic 'timber platform' at Star Carr to see whether a useful addition to the site archive could be produced. The level of detail recovered in this experiment was affected by the fact that the timbers had been exposed for more than a week and, although covered and kept wet, had suffered surface oxidation; the area was not completely drained prior to modelling, to minimise any risk from water flow through the underlying deposits (Figure CS5.12). The small sensor and fish-eye lens used in a GoPro camera would not be the first choice to achieve detailed high-resolution images, but the very low altitude at which the images were captured meant sufficient detail was obtained to produce a high-quality model without adversely affecting the site. The fish-eye lens meant that photographs taken from a vertical position at very low elevations recorded not only the upper surfaces of the timbers but also the sides of adjacent pieces. The lens characteristics of the GoPro are so well understood that Agisoft Photoscan was able to process the images without any prior image correction. The images for this model were collected in a single session of less than an hour and processed overnight to produce a scaled ortho-image, this was then printed on waterproof draughting film and used for recording annotations directly in the field as the timbers were lifted.

There is no doubt that using photogrammetry has the potential to transform the archaeological recording and excavation process, even if we have to modify the traditional workflow. Photogrammetric recording does not replace traditional methods, but it allows us to combine digital modelling of excavations in progress with drawings to articulate our interpretation of the evidence rather than serve as poor reflections of what we see, and offers the potential of a new approach that by saving time at the primary documentation stage can free up time for more detailed and careful observations during fieldwork and thus improve the quality of the excavation results.

Figure CS5.12
Star Carr, North Yorkshire. A timber platform modelled using an SUA controlled from several metres away to reduce any impact from deformation, which could arise if collecting the images while walking between the fragile waterlogged timbers or close by on the side of the trench.
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Case Study 6: Underwater photogrammetric survey

Structure from motion: a diver-based approach to photogrammetric survey.

Developments in the capabilities of multi-image photogrammetry have been enormously important for archaeologists, allowing practical and low-cost solutions for survey of terrestrial archaeological sites. However, it is within the discipline of underwater archaeology that that photogrammetric advances have had the greatest impact. The reasons for this are simple: the logistical demands of underwater archaeology in terms of time, cost, complexity and safety are much higher than they are for the terrestrial equivalent, and the use of photogrammetry can allow much faster and denser data capture than has previously been possible. In addition, alternative methods for the capture of similar data have been far more limited for underwater archaeology. Terrestrial laser scanning produces broadly similar results as multi-image photogrammetry and has been available to archaeologists for many years; despite promising early indications, laser-based technology has yet to offer a cost-effective mainstream practical methodology for underwater survey. While sonar surveys are excellent for large area coverage, they generally are not applied at the sub-metre scale and do not capture colour data.

Photogrammetry can also be used to produce realistic three-dimensional (3D) models that support dissemination of the results of archaeological projects to the wider public, and this is an area where underwater archaeology has benefited to a proportionally greater degree because the sites clearly are not accessible to the vast majority of the non-diving public. It is now becoming possible to bridge this gap through data-driven 3D reconstruction and virtual reality. Although 3D reconstruction has been possible for many years, the dense and textured surface capture of underwater photogrammetry allows communication of the visual experience of visiting an underwater site with an authenticity previously impossible using the more familiar artistic and subjective reconstructions. Essentially the public can now see and interact with underwater

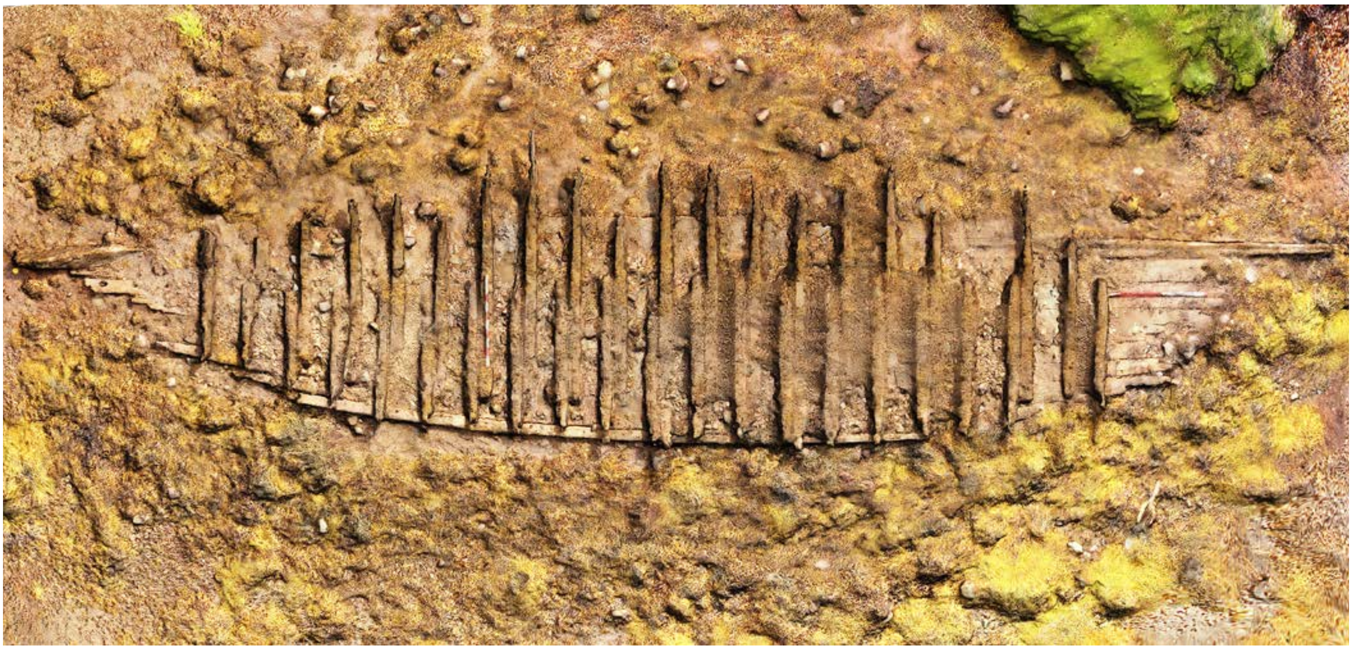

Figure CS6.1
Photogrammetric models of an intertidal shipwreck at Ardno, Loch Fyne, Argyll and Bute.
© Wessex Archaeology, John McCarthy

archaeology in a way that is much more akin to the actual experience of diving on the site. Finally, the technique has proven to be highly effective for recording intertidal archaeology, where rapid recording is essential because the sites are only accessible for a short period of time (Figure CS6.1).

Maritime archaeologists are still exploring the methodologies and applications of underwater photogrammetry. However, even within the last 5 years it has been demonstrated that entire shipwrecks can be recorded using this technique in a single day, an output that would have required hundreds of hours of underwater work setting up survey grids and using trilateration. A variety of approaches have been developed and current workflows vary from those requiring complex custom-built rigs costing hundreds of thousands of pounds to simple diver-held consumer-grade compact cameras in a waterproof housing.

There are a number of specific challenges to the practice of photogrammetry underwater. These include:

- reduced camera field of view and optical characteristics of the lens because of air to water light refraction
- low light levels
- limited and varying degrees of visibility through the water column
- loss of part of the colour spectrum (mainly red) in proportion to the depth plus distance from subject
- suspended particulates in the water column (affecting autofocus)
- dappling of light near the surface (caustics)
- the need to avoid disturbing sediment, particularly when photographing at low angles
- the presence of moving marine life, including fish and kelp.

In addition to the normal requirements of photogrammetric survey (adequate coverage and overlap, etc) the effects of each of these environment-specific factors must be carefully considered and accounted for when planning a photogrammetric survey underwater. In one regard photogrammetry is actually made easier under the water: divers with good buoyancy control can position themselves freely over the site, whereas ladders or small unmanned aircraft (SUA) might be needed for a similar site on land.

As with any photogrammetric survey, it is necessary to be aware of the pitfalls of the technique, particularly with regard to metric accuracy. The loss of visibility over distance when working underwater means that photos must be taken within a certain maximum distance from the subject (usually between 0.5 and 10m in UK waters). Underwater surveys can accumulate error more easily over distance without the possibility of correcting this using wider shots taken from further away, a technique that can be used to help correct surveys on land. It is also important to realise that photogrammetry can be difficult to apply to many archaeological underwater sites, because they lie in areas with generally poor through-water visibility or because they are covered in marine life that is in constant motion. In some cases kelp can be removed, but this is laborious and it may also threaten the stability of certain sites where the kelp helps to reduce water currents and their roots help to stabilise the archaeological matrix. However, when conditions are right, with clear water, good lighting and a site that is free of marine life, the results can be astounding!

Two examples of archaeological photogrammetry undertaken in the UK will be used to illustrate a simple diver-based approach.

Gun Rocks, Northumberland

In the 1970s, divers from the Tyneside 114 British Sub Aqua Club (BSAC) discovered a large number of cannons on the seabed at Gun Rocks, a small outcrop in the Farne Islands, off the coast of Northumberland. The site is thought to represent a wreck of 18th century date and mainly comprises a collection of 19 cannons lying on rocks and sand at a depth of 15m. In summer 2013, on behalf of English Heritage and with the assistance of Tyneside 114 BSAC, Wessex Archaeology investigated the site as part of the Heritage at Risk programme (Knott 2013). As well as traditional survey and sonar survey, the opportunity was used to undertake photogrammetric survey on three of the cannons as through-water visibility was excellent at over 5m. The cannons and rocks around them were covered in dense kelp; as the kelp was not a key factor in protecting the integrity of the site, it was manually cleared from the three cannons and their immediate surroundings during a single dive. The photogrammetric survey was then undertaken in an oval pattern around each cannon, maintaining a distance from camera to subject of approximately 1m. The 3D model results (Figures CS6.2–5) proved highly detailed and corresponded with manual measurements, and also proved suitable for further analysis. They were later shared with ordnance experts leading, to a new interpretation of one of the cannons and further evidence of the possible date of the wreck and the purpose of its final journey. Models were uploaded to online interactive portals to allow members of the public to explore the site in the same way).

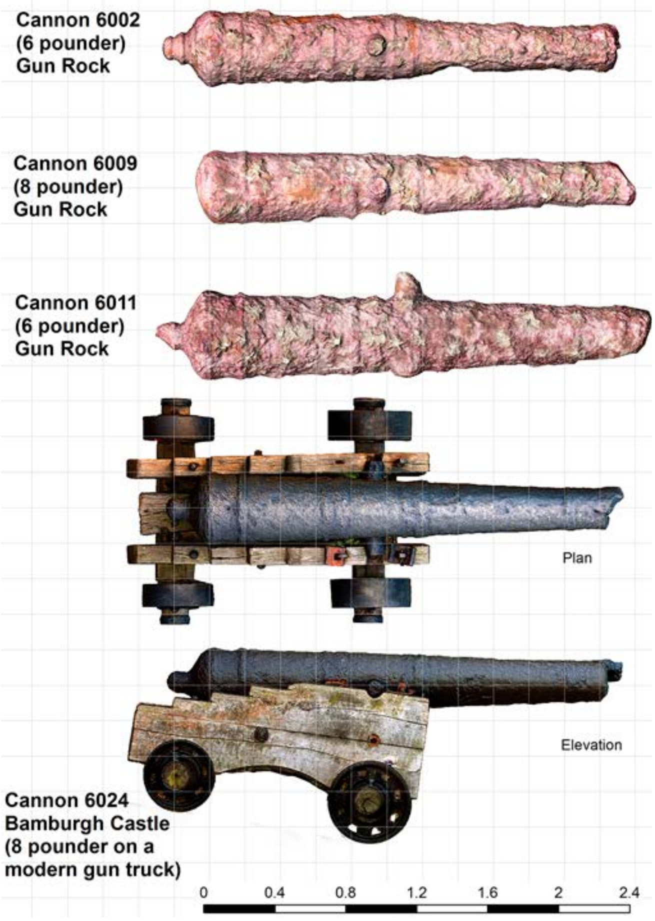

Figure CS6.2
Photogrammetric models of three cannons from Gun Rock, Farne Islands, Northumberland, and one recovered cannon on dry land.
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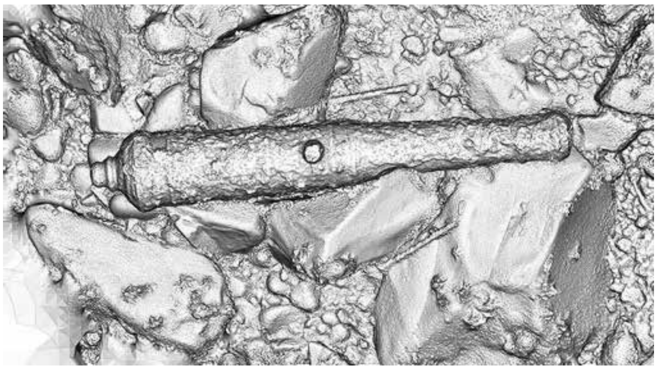

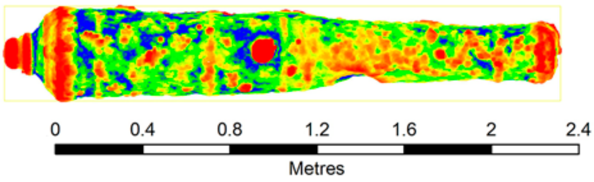

Figure CS6.3 (top)
Surface enhancement of a 3D model of cannons from Gun Rock, Farne Islands, Northumberland.
© Wessex Archaeology, John McCarthy

Figure CS6.4 (bottom)
Radial surface analysis of a 3D model of cannons from Gun Rock, Farne Islands, Northumberland.
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Drumbeg, Sutherland

The Drumbeg wreck site was discovered by scallop divers off the north-west coast of Scotland in the 1990s. The site was first reported and archaeologically surveyed in 2012 (McCarthy 2012), when it was found to consist of three cannons lying together over a section of hull together with two anchors lying at some distance away. The wreck has been tentatively interpreted on typological grounds as a possible Dutch trader of 17th century date. The site lies in an area of open sand at a depth of around 12m and through-water visibility is typical of the west coast of Scotland and is often over 5m. The site has been subject to photogrammetric survey twice, first in 2012 (McCarthy *et al* 2015), when the individual cannons were surveyed at close range, and again in 2014, when a large area survey

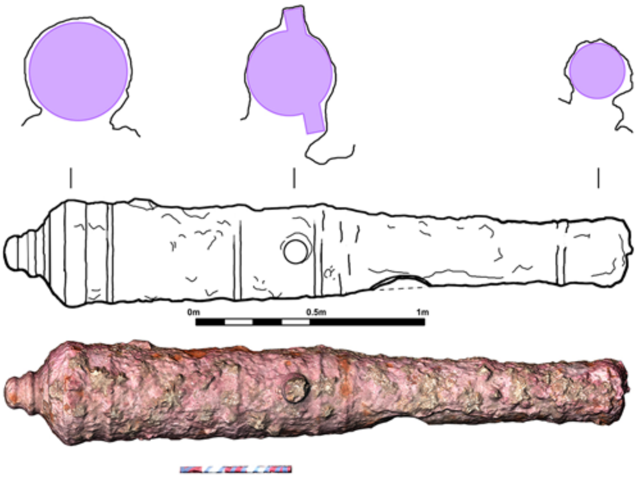

Figure CS6.5
Line drawing and volumetric calculations of cannon 6002.
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Figure CS6.6
A still from an animated reconstruction of the cannons at the Drumbeg wreck site.
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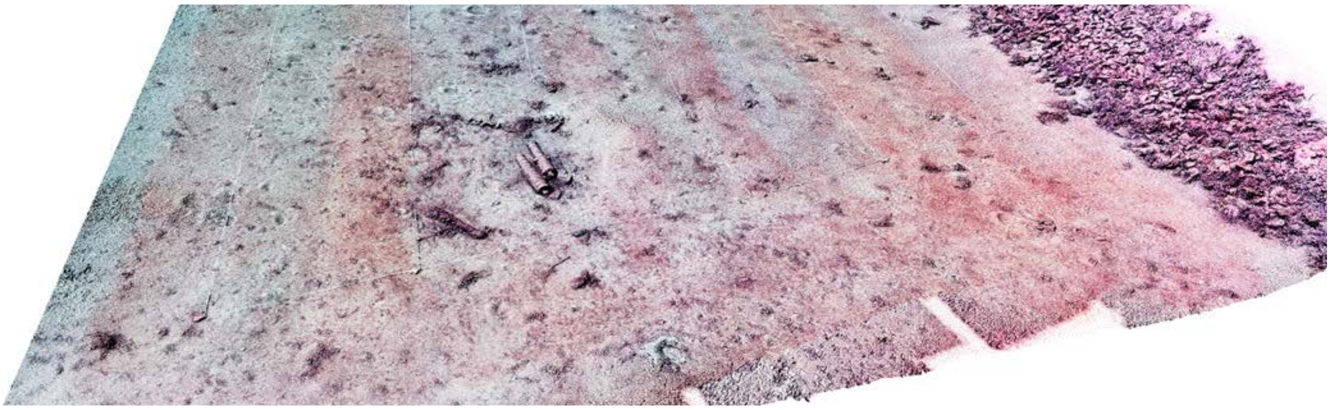

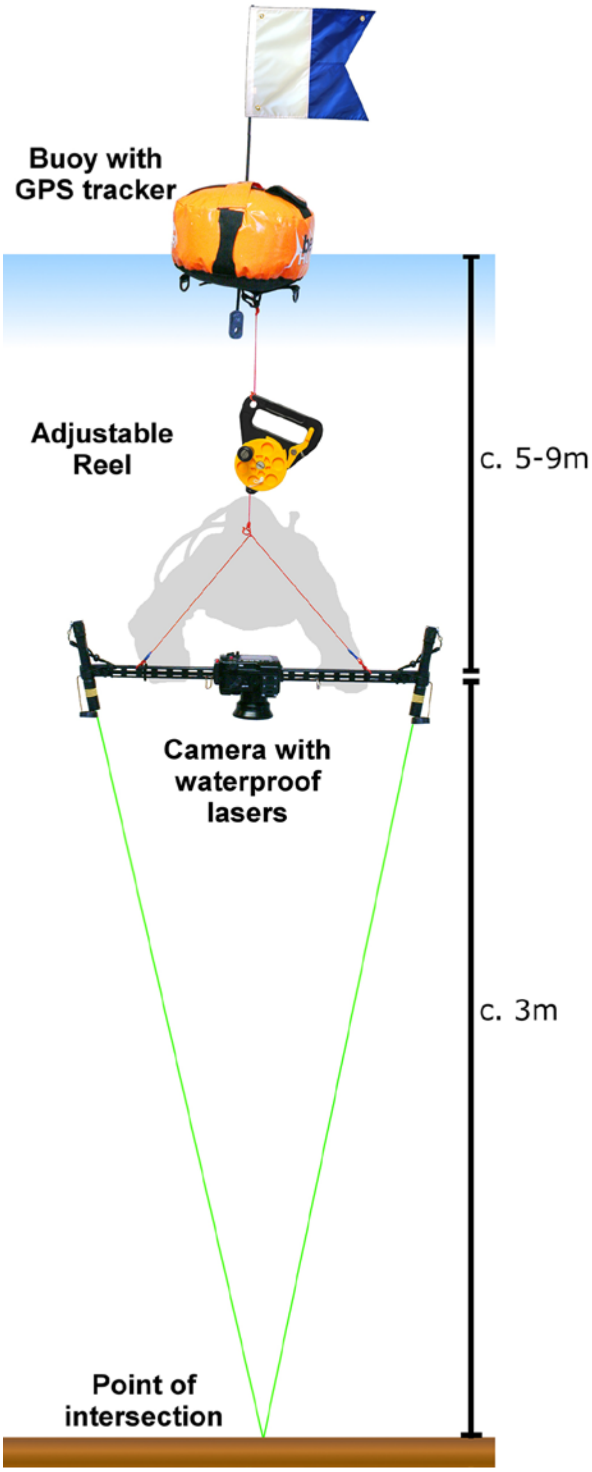

Figure CS6.7 (above)
Photogrammetric wide-area survey of the Drumbeg wreck site, Sutherland, covering an area of 35m^2.
Crown Copyright Historic Environment Scotland, John McCarthy

Figure CS6.8 (left)
A simple rig for maintaining a constant distance to the seabed.
Crown Copyright Historic Environment Scotland, John McCarthy

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was undertaken. The first survey's methodology was largely similar to the Gun Rocks example, but additional reconstruction of the cannons and anchors was undertaken, drawing on the 3D survey data (McCarthy and Benjamin 2014, Figure 6; Figure CS6.6). The second survey was principally a sub-seabed sonar and magnetometer investigation undertaken in order to establish whether the remains extended further than was visible on the seabed. At the same time a wide-area photogrammetric survey was undertaken in order to provide a wider context for the site, and the results demonstrated the possibilities for such larger surveys. In this case an area of approximately 35m^2 was captured to sub-centimetre detail in a single 40min dive (Figure CS6.7). Maintenance of a constant distance to the seabed was ensured through the use of a simple custom rig with laser pointers rigged to a surface buoy that intersected at a predetermined distance (Figure CS6.8).

Case Study 7: Modelling small objects

Introduction

This case study illustrates the process of imaging a very small object in order to provide a metrically accurate model for three-dimensional (3D) printing and display purposes. The object surveyed was a Roman coin, a Denarius of Nerva (accession number 768543), held in the English Heritage collection at Wrest Park (Bedfordshire). The brief was to create 3D models of some of the finds in the Wrest Park archaeological store that were of sufficient quality to be 'blown up' and 3D printed. The 3D prints were to be used for educational visits and handling, including, for example, the creation of rubbings. The quality and resolution of the models needed to be such that they would withstand an increase in size from approximately the size of a five-pence piece to a dinner plate. However, the purpose of the 3D print was to produce a hardwearing replica that, while being recognisable and accurately depicting the source artefact, did not have to be of museum replica quality.

Cameras and lenses

In order to image such a small object it was decided to use macro lenses. Two cameras were used: a Nikon D800 (36MP) with a fixed focal length 200mm Nikkor macro lens, and a Sony Alpha 7R II (42MP) with a fixed focal length Sony 90mm macro lens. The Nikon setup was used for close-up images of the coin itself, while the Sony setup was used to provide slightly wider context-setting shots, which included ancillary objects such as scale bars and colour reference cards.

Both cameras were tripod mounted, with a 5s shutter delay to allow the camera to settle before the image was exposed. The Nikon setup required an aperture of f/16 in order to keep as much of the subject in focus as possible. The Sony setup used an aperture of f/11.

Lighting

In order to provide consistent ambient light to minimise shadows being cast, an object photography tent was used (Figure CS7.1).

Figure CS7.1
The tent and lighting setup used.

Such tents are highly portable (folding down into a small flat package that is lightweight), relatively cheap and can be deployed in seconds. They are used in conjunction with an external LED lighting rig, which can be left on for the duration of the shoot. The light is diffused by the material of the tent and produces conditions inside, where the object is placed, suitable for taking consistently lit and shadow-free images.

Other equipment

The coin was placed on an automatic turntable that could be controlled via an app on a smartphone. There are several advantages to using an automatic turntable, for example manual intervention to turn the object after each exposure is not required, and the number of stops the turntable makes can be controlled to give, say, 12, 36 or 72 imaging positions for each full rotation. For this object, 36 images per revolution was selected.

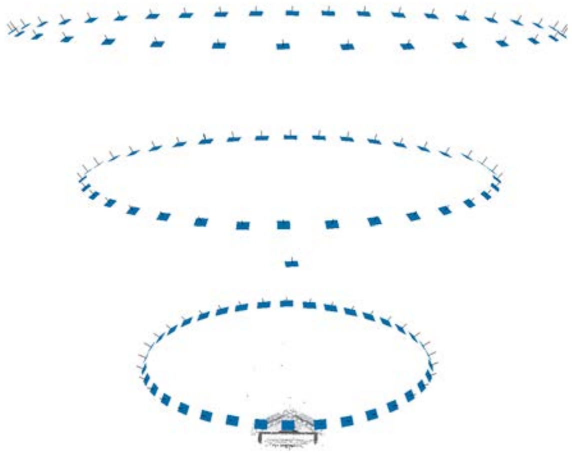

Figure CS7.2 (top)
Scales and grey card next to the object during photography.

Figure CS7.3 (bottom)
The imaging strategy used for each half.

Other objects were placed adjacent to the coin (Figure CS7.2), and a forensic scale, with a manufacturer's quoted accuracy of 0.1mm, was used to provide scale and orientation for each model. One shot was taken with a full-colour reference card and a grey card in view. The grey card was left in for all subsequent photography because removing it was not necessary.

Imaging strategy

Figure CS7.3 illustrates the imaging strategy. The obverse and reverse faces of the coin were imaged separately. Three rings of photography were taken for each side, with 36 images in each ring, and a vertical shot was taken with the camera directly over the coin, offset from the tripod on a bar. The edges of the coin, best represented in the lowest ring of imagery, were shot with the 200mm macro lens. Very small, but clearly visible, points on the edges were later used to match the two halves of the coin together. Many of these points were not visible to the naked eye but, after taking some test images, it became clear that enough of them were discernible for matching. Images were shot in RAW on both cameras.

Processing

White balance was applied during RAW processing to uncompressed TIFF format. The images were then renamed according to local archival convention and metadata added. No other pre-processing was applied.

Photogrammetric processing was carried out using Agisoft Photoscan Professional. Images were examined and out-of-focus areas masked. The images were aligned, and a medium-quality dense cloud and mesh produced. This allowed for the semi-automated identification of the targets on the scales. After adjusting their positions in the images as necessary, the control points were given coordinate values and the alignment optimised. The model for each face of the coin was then scaled correctly. The reconstruction region was adjusted inwards to include only the coin. The dense cloud and mesh were recomputed using high-quality settings. The resulting meshes had face counts of *circa* 2 million polygons after trimming out any extraneous geometry such as the surface of the turntable.

The chunks representing the two halves were then duplicated to avoid having to reprocess them, and subsequent work took place on the copies. The intention was to match the two halves of the coin using a marker-based approach, ie identifying common points on both models, which were only around the edges, and using them to align the two models correctly. Existing control points for the two halves were removed, as they would have had an adverse effect on correct alignment. Markers were added (Figure CS7.4), again in a semi-automated process, which required only the subsequent removal of markers where they were not visible. The two halves were then aligned using the marker-based method while keeping their scale fixed, correctly placing them relative to each other.

The two models were exported as .ply format files to Geomagic Wrap. This was necessary because the models were intended for 3D printing, for which the meshes would require some additional editing to make them suitable. It was also so that the polygons in the meshes representing the two halves could be stitched together to produce a single seamless model with no holes or artefacts likely to cause problems in the 3D printing process, such as self-intersections in the mesh.

In Agisoft Photoscan, the models of the two halves, now aligned, were merged to form a new model of both halves. The mesh was deleted and replaced with the edited model from Geomagic, which was on the same coordinate system and at the same scale (Figure CS7.5 shows the final model).

Products

The wider project (the coin was one of several objects being modelled) has yet to be finished (May 2017). The coin is to be 3D printed at an enlarged scale, and used for online presentation via the Sketchfab website. The two dissemination methods have different requirements in terms of polygon count. Higher polygon count models are necessary for the 3D printing, especially as it involves enlarging the object, while relatively low polygon count models are suitable for online viewing. The combined mesh model was therefore duplicated for decimation to a number of different polygon target counts for the different outputs, and each model textured before export.

Figure CS7.4 (top)
Markers used to match the two halves of the model.

Figure CS7.5 (bottom)
The final complete model.

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Software

Software mentioned in the text; this is not an endorsement.

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3DF Zephyr		http://www.3dflow.net/3df-zephyr-pro-3d-models-from-photos/
3DHOP		http://3dhop.net/
Aerial	John Haigh	jghaigh@aerial5.co.uk
Airphoto	Irwin Scollar	http://www.uni-koeln.de/~al001/airdown.html
Arc3D	KU Leuven	http://www.arc3d.be
ArcGIS	ESRI	http://www.esri.com/arcgis/about-arcgis
Bundler		https://github.com/snavely/bundler_sfm
Cloud Compare		http://www.danielgm.net/cc/
ContextCapture	Bentley	https://www.bentley.com/en/products/product-line/reality-modeling-software/contextcapture
Correlator 3D	SimActive	http://www.simactive.com/en/
Cyclone	Leica	http://leica-geosystems.com/en-gb
Drone Deploy		www.dronedeploy.com
Erdas Imagine	Hexagon	http://www.hexagongeospatial.com/products/power-portfolio/erdas-imagine
GRASS		https://grass.osgeo.org/
Lidar Visualisation toolbox		http://www.arcland.eu/outreach/software-tools/1806-lidar-visualisation-toolbox-livt
Meshlab		http://meshlab.sourceforge.net/
Netfabb		https://www.autodesk.co.uk/products/netfabb/overview
Photomodeler		http://www.photomodeler.com/index.html
Photoplan	FARO	http://www.faro.com/products/construction-bim-cim/faro-photoplan/
Photoscan (Pro)	Agisoft	http://agisoft.com/
Pix4D mapper		https://pix4d.com/
QGIS		http://www.qgis.org/en/site/
QT modeller		http://appliedimagery.com/
RealityCapture		https://www.capturingreality.com/
Recap 360	Autodesk	https://www.autodesk.com/products/recap/overview
Recap Image	Autodesk	https://www.autodesk.com/products/recap/overview
Relief Visualisation Toolbox (RVT)		http://iaps.zrc-sazu.si/en/rvt#v
Scene	Faro	http://www.faro.com/en-us/products/faro-software/scene/overview
Sketchfab		www.sketchfab.com
Visual SfM		http://ccwu.me/vsfm/

Other web resources

Aerial Archaeology Research Group (AARG)	http://www.univie.ac.at/aarg/
Archaeology Data Service (ADS)	http://archaeologydataservice.ac.uk/era/section/record_manage/rm_projects_nadrap_home.jsf
Bing maps	https://www.bing.com/maps
CAA	www.caa.co.uk/uas
GSD calculator	https://support.pix4d.com/hc/en-us/articles/202560249-TOOLS-GSD-Calculator
International Centre for the Study of the Preservation and Restoration of Cultural Property (ICCROM)	http://www.iccrom.org/
International Society for Photogrammetry and Remote Sensing (ISPRS)	http://www.isprs.org/
Kite Aerial Photography	http://www.kiteaerialphotography.org.uk/
Royal Institution of Chartered Surveyors (RICS)	https://www.rics.org/uk/
Remote Sensing and Photogrammetry Society (RSPSoc)	http://www.rspsoc.org.uk/

6 Glossary

2.5D
Notation used to describe points, or a surface made up of points, that have plan coordinates and a height value but are not part of a true 3D surface; there is no possibility of undercuts.

360 degree camera
A camera that can produce a cylindrical image with one exposure either using multiple lenses or by using one lens that automatically pans around 360 degrees.

Absolute accuracy
The accuracy with respect to a defined coordinate system.

AF
Auto-focus.

Affine transformation
A transformation that will fit any three points, in 3D space, to any other three. Angles and distance between the points will not be maintained but parallelism between any two lines will be.

AGL
Above ground level.

Aperture
The, usually, adjustable opening through which light passes into a camera.

Bayer array
The particular arrangement of colour filters used in most digital camera sensors; there are twice as many green filters as red or blue; see also CFA.

Bits
The basic unit of information in computing; it can have only one of two values.

Bowl effect
The situation where a computed model or surface bends up at the sides or ends as a result of accumulated errors, so that it is not as flat as it should be.

bpp
Bits per pixel; the higher the value, the more colour variation is encoded in an image.

Breaklines
Lines used to define sharp changes of slope in a DEM.

Bundle adjustment
A process that adjusts the ‘bundles’ of rays between each camera centre and a set of projected 3D points until a minimal discrepancy between the positions of the observed and re-projected points is achieved.

Bundle block adjustment
Bundle adjustment applied to a block of images, ie a number of strips.

BVLOS
Beyond visual line of sight. The distance beyond which it would not be possible to see an SUA.

CAD
Computer-aided design.

Calibrated focal length
An accurately measured focal length.

Camera shake
see motion blur

CFA
Colour filter array. An arrangement of colour filters on a digital camera sensor that means certain image diodes only receive particular colours. The resulting colour channels, eg RGB, are used to form the final image.

Channel
The units of separation of a digital image, eg RGB.

Chief ray
A light ray that theoretically passes in a straight line from the object point through the perspective centre of the lens and onto the image plane of a camera.

Chromatic aberration
The result of variation in the focusing of different colours on an image sensor leading to noticeable coloured fringes.

Clipped tonal curve
The result of capturing an image where the intensity of certain parts is outside the range that can be represented. This can lead to, for example, clipped highlights, where the full range of brightness in the subject is not apparent in the resultant image.

Collinearity
The situation in which a number of points lie on the same single straight line.

Colour saturation
The intensity of a particular colour in an image. The primary colours, red, yellow and blue, are fully saturated.

Colour temperature
An expression of the colour of a light source based on the colour of a theoretical black body when heated to a certain temperature (degrees Kelvin). A reddish-yellow white light is cooler than a bluish white light, while daylight has the highest colour temperature.

Control
Points with known coordinates used to position or constrain a plan or 3D model.

Convergent
In the case of photogrammetry, the situation where the camera axes are not parallel, ie they are pointing towards the same part of the subject.

CT scanner
Computed tomography scanner. An instrument that generates 3D images by combining numerous slices of an X-ray image.

Decentring lens distortion parameters (p1, p2)
see tangential distortion

DEM
Digital elevation model. A digital representation of a surface. DSM and DTM are types of DEM.

Depth of field
That portion of the field of view of a camera that will be in focus for a particular aperture setting. A smaller aperture gives a greater depth of field.

DGPS
Differential GPS. A way of improving the accuracy of coordinates collected with a GNSS by using two receivers, one of which is located at a known point. The relative accuracy between the two receivers will be high so that the data collected by the fixed receiver can be used to correct that captured by the moving one. The fixed receiver is often replaced by a virtual signal transmitted from a server.

Diffraction limit
The point beyond which loss of sharpness because of diffraction becomes unacceptable when reducing aperture size.

Dishing effect
see bowl effect

dpi
Dots per inch. A definition of the resolution of an image originally used by the printing industry where the dots are dots of ink. In a digital image the dots are analogous to pixels; the higher the dpi, the more detail is represented in the image.

Drone
see SUA

DSM
Digital surface model. For landscapes, the DSM is the surface including features such as buildings and trees, while the DTM represents the ‘bare earth’ surface resulting from the filtering out of these features.

DTM
Digital terrain model. For landscapes, the DTM represents the ‘bare earth’ surface resulting from the filtering out of features such as buildings and trees, while the DSM is the surface including features such as buildings and trees.

Dynamic range
The ratio between the maximum and minimum luminance in an image. In a high dynamic range image, a greater range of luminance will be correctly exposed.

E57
A non-proprietary format for point cloud data, developed by the American Society for Testing and Materials.

EGNOS
European Geostationary Navigation Overlay Service. A form of differential GPS where the corrections are transmitted from geostationary satellites.

Electronic front and rear curtain
A feature in some digital cameras that in effect speeds up the opening and closing of the shutter by sequentially activating the image diodes just ahead of the movement of the physical curtain.

EXIF
Exchangeable image file format. A standard for digital image metadata such as date and exposure information.

Exposure
The act and associated settings of opening the shutter in a camera to expose the sensor to light; also used to describe the result of opening the shutter, ie an image.

f/number, f/stop
In effect the size of the aperture used for a particular exposure, but more correctly the ratio of the focal length of a camera lens to the diameter of the aperture.

FAPAR
Fraction of absorbed photosynthetically active radiation. A method of quantifying the amount of solar radiation absorbed by leaves for photosynthesis.

Fast lens
A lens that has the ability to use a larger aperture (eg f/1.2), so, ie more light will enter the camera during a shorter exposure time.

Fiducial marks
Marks that appear in the frame of an analogue metric camera to enable correction of film distortion and placement of the image in a photogrammetric instrument.

Firmware
Software permanently programmed into a piece of equipment.

Fish-eye lens
An ultra-wide angle lens, usually giving a field of view of 180 degrees or more.

Flat lighting
An arrangement of lights that results in little or no shadow on the subject.

Focal length
The distance between a lens and the image sensor when the subject is in focus.

F*x* and F*y*
Focal length in pixels. Although a lens has only one focal length, F, if the pixels on camera sensor are rectangular then f*x* and f*y* are F multiplied by the number of pixels per unit length along each axis.

GCPs
Ground control points. Control points used in the mapping of landscapes from aerial platforms.

GIS
Geographic information system. A database where the information is related to a map or other graphical representation of the surface of the Earth.

GNSS
Global navigation satellite system. A system that enables surveying or navigation by reference to a number of satellite constellations.

GNU
A free computer operating system.

GPR
Ground-penetrating radar. A geophysical process that uses radar pulses to image surfaces below ground.

GPS
Global positioning system. A generic term used to describe surveying or navigation by reference to a satellite constellation, although it is specifically the name for the satellite constellation operated by the USA; see also GNSS.

Ground-truthing
The process of verifying remotely sensed data by checking (a sample of) the findings on the ground.

GSD
Ground sample distance. The distance on the ground or subject that is represented by the distance between adjacent pixel centres in an image.

GUI
Graphical user interface. The means by which the user communicates with most software.

Hachures
Symbols used to indicate direction and steepness of slope on a map or topographic survey.

Hand-drawn survey
Survey undertaken using on-site drawing and hand measurement, usually with a tape measure.

HDR
High dynamic range; see dynamic range.

Height displacement/distortion
Errors in an image caused by variation in the relief of the subject. Those parts of the subject nearer the camera will be at a larger scale than those further away and their position will also be more adversely affected by tilts of the camera.

Hillshade
A method of depicting slope in a graphical representation of a landscape.

Histogram equalisation, histogram stretching
A method for improving the contrast of a digital image.

Hot mirror
A filter normally used to protect optical systems from infra-red radiation.

Hot shoe
A connector, usually on the top of a camera, to allow the mounting of ancillary equipment such as a flash gun. The term ‘hot’ refers to the fact that the mount enables the firing of the flash in synchronisation with the shutter release.

Image diodes
The individual receptors in an image sensor; analogous to the pixels in the resultant image.

Image distance
The distance between a point on the subject of a photograph and the image plane.

Image noise
Unwanted variations in an image resulting from the signal noise in the sensor.

Image pair
see stereo pair

Image plane
That part of a camera where the image is projected and recorded, either onto film or a sensor.

Image point
The point on an image representing a specific point on the subject.

Image rectification
see rectified photography

Image triangulation
A technique used to calculate the relative position for each image in every pair in a strip of images.

Inner or interior orientation The process of determining the internal characteristics of a camera system, such as the focal length and lens distortion.

INS
Inertial navigation system**.** A computerised system using accelerometers and gyroscopes to calculate, by dead reckoning, the path of a vehicle on which it is mounted.

IPs
Interest points. Points on an image identified by photogrammetric software for the image-matching process.

IS
Image stabilisation. A system inside a camera that moves the sensor while the shutter is open in an attempt to reduce motion blur.

ISO value
International Standards Organisation value. A standard for describing image sensor sensitivity to light, analogous to film speed. The higher the ISO value, the less light is required for the same exposure.

Key points
see IPs

KML file
A version of XML developed for viewing geographical data in Google Earth.

Landsat
A satellite system developed by the National Aeronautics and Space Administration (NASA) to provide imagery of the surface of the Earth for resource management purposes.

Laser scanner
A laser device that collects 3D coordinates of a given region of a surface automatically and in a systematic pattern at a high rate (thousands of points per second), achieving the results in (near) real time.

Lens distortion
Distortion of an image caused by characteristics of the lens.

Lidar
Light detection and ranging. A system that uses laser pulses to measure the distance to an object or surface, typically determining the distance by measuring the time delay between transmission of a pulse and detection of the reflected signal.

Luminance
The intensity of light emitted from a surface per unit area.

Macro lens
A lens that results in an image with a scale of 1:1 or larger.

Mesh
A method of digitally representing a surface using points connected by lines to define a large number of smaller polygons (usually triangles or squares).

Metadata
Data about data, eg exposure information for a digital image.

Metric camera
A camera with a calibrated lens.

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Mirror lock-up mode
The situation where the mirror in a single lens reflex camera is moved and locked out of the image path before the shutter is opened. This removes a source of possible camera shake.

Mirrorless camera
A camera where there is no mirror, to allow a through-the-lens viewfinder. The viewfinder is either digital or uses separate optics.

Motion blur
Blur in an image caused by movement of the camera (camera shake) during exposure.

MP
Mega-pixel.

MVS
Multi-view stereo. A photogrammetric process using multiple convergent images.

NDVI
Normalised difference vegetation index. A method for measuring vegetation health where a near infra-red channel is used in addition to the red channel in a RGB image. In essence, NDVI = (NIR-red)/(NIR +red).

NIR
Near infra-red.

NIR pass filter
A filter that allows NIR radiation to pass through it.

Object point
The point on the subject of a photographic image represented by the image point on the sensor.

Open GL
The industry-standard graphics programing language.

Orthogonal projection
A method of representing a 3D subject where all the projection lines are at right angles (orthogonal) to the projection plane.

Ortho-images
Images resulting from an orthogonal projection.

Perspective centre
The point of origin or termination of bundles of rays or projecting lines directed to a point object in a camera system, effectively the projection centre of an ideal camera.

Perspective correction lens
see tilt-shift lens

Perspective distortion
Distortion of the subject of an image caused by the use of a perspective projection, as opposed to an orthogonal projection.

Photo-diodes
see image diodes.

Photogrammetric reconstruction
The process of producing a model using photogrammetry.

Pixel
The smallest element of a digital image, analogous to an image diode in a digital camera sensor.

Point cloud
A set of, usually many, points in a 3D coordinate system used to represent the surface of a subject.

Post spacing
The distance between points in a DEM or point cloud.

Posterisation
The reduction in tonal range of an image resulting in sharp changes of colour. The term refers to a deliberate act to facilitate the printing of posters.

ppm
Parts per million.

Prime lens
A fixed focus lens.

Principal distance
The equivalent of the focal length of a camera.

Principal point
The point where a straight line passing through a lens at right angles to the imaging plane meets that plane.

Principal point offset
The extent to which the principal point is not in the centre of the image plane.

Projection centre
The theoretical centre of a camera lens system through which all light rays from the subject pass before arriving at the sensor.

Quantisation
A matrix that controls the compression ratio of, for example, a JPG image.

Radial lens distortion parameters (k1, k2, k3, k4)
Distortions that vary with distance from the centre of the lens.

RANSAC
RANdom SAmple Consensus. An algorithm for detecting outliers in a set of points.

Raster image
A digital image composed of individual pixels; a straight line will be represented by several pixels, whereas in a vector plan it will consist of two connected points.

RAW format
Various proprietary image formats (not an acronym) containing minimally processed data from an image sensor. The files need to be post-processed to produce images in common formats, which means exposure, colour adjustments, etc, can be made. Each camera manufacturer has its own type of RAW file.

Rectification plane
The plane that a rectified image is corrected to fit. Any features in the image not on that plane will not be to the specified scale.

Rectified photography, rectified image
The process and image resulting from correcting a single image to fit a 2D plane.

Reference plane
see rectification plane.

Reflectorless
The ability of an electromagnetic distance measurement system, in, for example, a TST, to measure to any surface rather than just to a prism.

Relative accuracy
The accuracy of one element of a survey with regard to another rather than a particular coordinate system.

Relief displacement
see height displacement.

Re-projection error
The geometric error as a result of the difference in image distance between a projected point and a measured point.

Resolution
The smallest interval measurable by an instrument such as a scanner or camera. Radiometric resolution refers to the number of different colours that can be captured, while geometric resolution refers to the physical size of the smallest measurable element.

RGB
Red, green, blue. The usual colour channels of a digital image.

Ring flash unit
A ring-shaped photographic flash that mounts around the lens, thus giving a more uniform illumination of the subject.

Rising front lens
see tilt-shift lens.

RMSE
Root mean square error. A statistical method of measuring the difference between the measured and predicted values of a sample; often used in surveying as an indication of accuracy.

RPAS
Remotely piloted aircraft system; see SUA.

Sensor
An electronic component or system for detecting particular values in its environment. In the case of cameras, the values will be for light.

Sensor sensitivity
The change in output of the sensor per unit change in the parameter being measured, eg for a digital camera the variation in colour required to give a different pixel value in the resulting digital image.

Shutter speed
A way to describe the length of time a camera shutter is open.

Side lap
The overlap between strips of photography.

SIFT
Scale invariant feature transform.
An algorithm for detecting similar features in a number of images; used in photogrammetric applications for image matching.

Signal noise
Unwanted and usually unknown variations that a signal may suffer in the collection process. This can occur during capture, transmission or processing.

Specular
Mirror-like.

Stand-off
The distance away from a subject that it is possible or desirable to take a measurement or image from.

Stereo pair
Two photographs with sufficient overlap for photogrammetric application.

Stereo photogrammetry
Photogrammetry that employs two rather than multiple images to calculate the position of the subject.

Stopping down
The act of reducing the camera aperture; increasing the f/number.

SUA
Small unmanned aircraft. Small aircraft weighing less than 20kg that are controlled remotely from the ground or with a pre-programmed flight path. They can be rotary, like a helicopter, or fixed-wing, like an aeroplane, and usually carry a camera or some other instrument.

Swath
In the context of aerial photography or lidar, the strip of ground covered by one pass of the aircraft.

Systematic error
Errors that are constant or a constant ratio, rather than random, and hence can be corrected for.

Tangential distortion
Image distortion resulting from the camera lens and image plane not being parallel.

Textured mesh
A mesh with an associated image that is mapped to the surface to provide a more realistic rendering of the subject.

Tie points
Points with unknown coordinates that can be used to tie together two elements of a survey, such as photogrammetric models.

TIFF
Tagged image file format. A non-proprietary digital image format.

Tilt-shift lens
A lens that can be tilted or shifted with respect to the image plane. Such lenses are generally used to correct the perspective effect in architectural photography.

TIN
Triangulated irregular network. A type of mesh made up of points joined by lines of varying length, resulting in triangles of various sizes and shapes.

Tonal curve
A curve on a graph representing the variations in tone in an image (from dark to light) of shadow, mid-tones and highlights.

Topographical relief
Variations in the shape of a surface; usually height in a landscape.

Trilateration
The determination of the position of a point by measuring three or more distances to other known points.

TST
Total station theodolite. A surveying instrument used to measure angles (vertical and horizontal) and distances and record them. Such instruments are known as total stations because all the data required is collected and stored in one self-contained system.

UAV
Unmanned aerial vehicle; see SUA.

Unsharp masking
A process available in some image-processing softwares for sharpening images. It refers to the use of a blurred negative of the image to create the mask.

Vector plan
A drawing or map made up of vectors, ie lines connecting points, rather than a raster image, where a straight line can be represented by numerous pixels.

Vectorisation
The act of converting a raster image into a series of vectors.

Viewshed
The part or parts a of landscape that are visible from a particular vantage point.

VR
Vibration reduction; see image stabilisation.

WGS84
World Geodetic System 1984. The coordinate system used by GNSSs that is often transformed to a particular national grid system for subsequent use.

White balance
The process of correcting colour balance in a digital image so that, for example, whites in the subject are actually white in the image.

Wide-angle lens
A lens with a shorter than normal focal length (35mm or less) that thus captures a wider field of view.

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