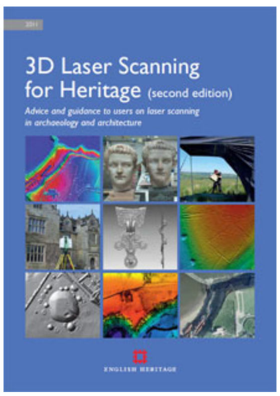
3D Laser Scanning for Heritage



On 1st April 2015 the Historic Buildings and Monuments Commission for England changed its common name from English Heritage to Historic England. We are now re-branding all our documents.

Although this document refers to English Heritage, it is still the Commission's current advice and guidance and will in due course be re-branded as Historic England.

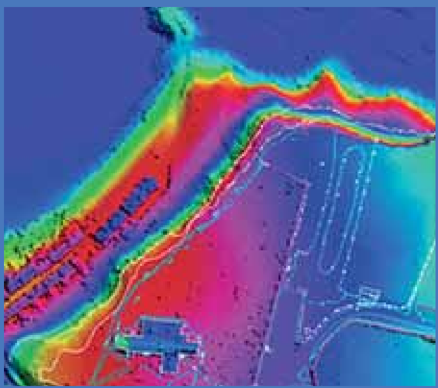
Please see our website for up to date contact information, and further advice.

We welcome feedback to help improve this document, which will be periodically revised. Please email comments to guidance@HistoricEngland.org.uk

2011

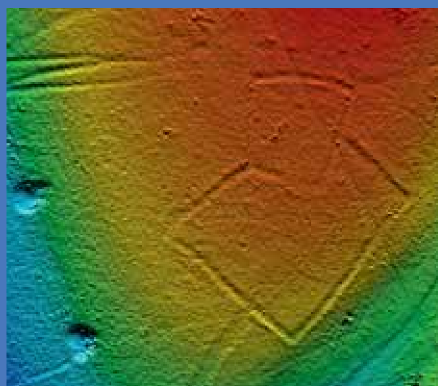
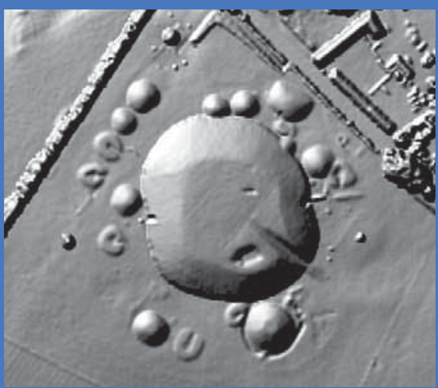
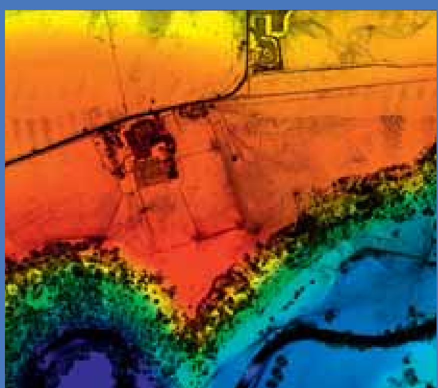
3D Laser Scanning for Heritage (second edition)

Advice and guidance to users on laser scanning in archaeology and architecture








ENGLISH HERITAGE

Preface

In October 2006 the School of Civil Engineering and Geosciences at Newcastle University completed a two-year project entitled 'Developing professional guidance – laser scanning in archaeology and architecture', supported by the Historic Environment Enabling Programme (now called National Heritage Protection Commissions) (3789 MAIN). The project, which adopted the working name 'Heritage3D', sought to provide guidance to archaeologists, local planning authorities, instrument manufacturers and software developers on the use of 3D laser scanning in the conservation of cultural heritage. The primary aims of this project were to develop and support best practice in laser scanning for archaeology and architecture, and to disseminate this best practice to users, along with the education of likely beneficiaries. A guidance note arising from Heritage3D, entitled '3D Laser Scanning for Heritage' was published in 2007.

The present document, a substantial revision of the 2007 guidance note, has been developed as part of the follow-on project. The aim of the second phase of the Heritage3D project (5496 MAIN; October 2008 to September 2011) is to provide, to English Heritage employees and other professionals engaged in cultural heritage, general news and independent information about all forms of 3D survey and recording, in-depth guidance and discussion on specific applications and techniques, and to provide access to a network of relevant organisations and individuals that could provide information and advice.

Contents

1 Introduction

1.1 Aims

The advice and guidance presented here aims to provide the reader with the information required to use laser scanning appropriately and successfully within heritage related projects. However, it should be noted that other survey techniques can provide three-dimensional information and should be considered alongside laser scanning. So, while this document presents information specifically about when, why and how you might want to use laser scanning, it also points to other techniques that might be usefully considered. Moreover, it covers generic issues – such as data management – where the advice and guidance given will be relevant to any metric survey technique. Through this guidance it is hoped that readers will be able to understand how laser scanning works, why they might need to use it and how it could be applied.

For further explanation of the abbreviations used in this document see the Glossary (page 19).

1.2 The Heritage3D project

This document has been generated as part of the Heritage3D project. Heritage3D is sponsored by English Heritage's National Heritage Protection Commissions programme (projects 3789 MAIN and 5496 MAIN) and undertaken by the School of Civil Engineering and Geosciences at Newcastle University. As part of its remit, the Heritage3D project has developed and supported best practice in laser scanning for archaeology and architecture, and disseminated this best practice to users, since 2004. Further details of the project can be found at the Heritage3D website, www.heritage3d.org. A summary of each case study is given at the end.

1.3 Three-dimensional recording

The recording of position, dimensions and/or shape is a necessary part of almost every project related to the conservation of cultural heritage, forming an important element of the documentation and analysis process. For example, knowing the size and shape of a topographic feature located in a historic landscape can help archaeologists identify its significance; knowing how quickly a stone carving is eroding helps a conservator to determine the appropriate action for its protection; while simply having access to a clear and accurate record of a building façade helps a project manager to schedule the work for its restoration.

It is common to present such measurements as plans, sections and/or profiles plotted on hardcopy for direct use on site. However, with the evolution of new methods of three-dimensional measurement, computer software ubiquity and literacy among users, there is a growing demand for three-dimensional digital information.

There is a variety of techniques available to generate three-dimensional survey information. These techniques can be characterised in a number of ways, but a useful method is by the scale at which they might be used (which is related to the size of the object they could be used to measure), and by the number of measurements they might be used to acquire (which is related to the complexity of the object). Fig 1 summarises these techniques in terms of scale and object complexity. While hand measurements can provide dimensions and positions of objects and scenes of a few metres in size, it is impractical to extend this to larger objects; and collecting many measurements (for example 1,000 or more) would be a laborious process. Close-range photogrammetry and terrestrial laser scanning could be used to provide a greater number of measurements for similar object sizes, and therefore, are suitable for more complex objects. Photogrammetry and laser scanning may also be deployed from the air so as to provide survey data covering much larger areas. While global navigation satellite systems (GNSS) might be used to survey similarly sized areas – the most commonly known system being the Global Positioning System (GPS) – the number of points it might be practical to collect is limited when compared to airborne, or even to spaceborne, techniques. This advice and guidance is focused closely on laser scanning (from the ground or from the air), although the reader should always bear in mind that another technique may be able to provide the information required. Moreover, it is most often the case that no single survey methodology will be utilised in isolation – GNSS, for example, will often be used to control airborne photogrammetry, while terrestrial laser scanning often relies on control provided by terrestrial survey instrumentation such as a total station. Laser scanning, whether from the air or from the ground, enables a large quantity of three-dimensional measurements to be collected quickly. This document presents advice and guidance on the use of laser scanning, so that archaeologists, conservators and other cultural heritage professionals unfamiliar with the approach can make the best possible use of this recently introduced, but now highly developed, technique.

The term 'laser scanner' is generally applied to a range of instruments that operate on differing principles, in different environments and with different levels of precision and resulting accuracy. A generic definition of a laser scanner, adapted from Böhler and Marbs (2002) is 'any device that collects 3D co-ordinates of a given region of an object's surface automatically and in a systematic pattern at a high rate achieving the results in near real time' (Böhler, W and Marbs, A 2002 '3D Scanning Instruments'. *Proceedings of CIPA WG6 Scanning for Cultural Heritage Recording*, September 1–2, Corfu, Greece).

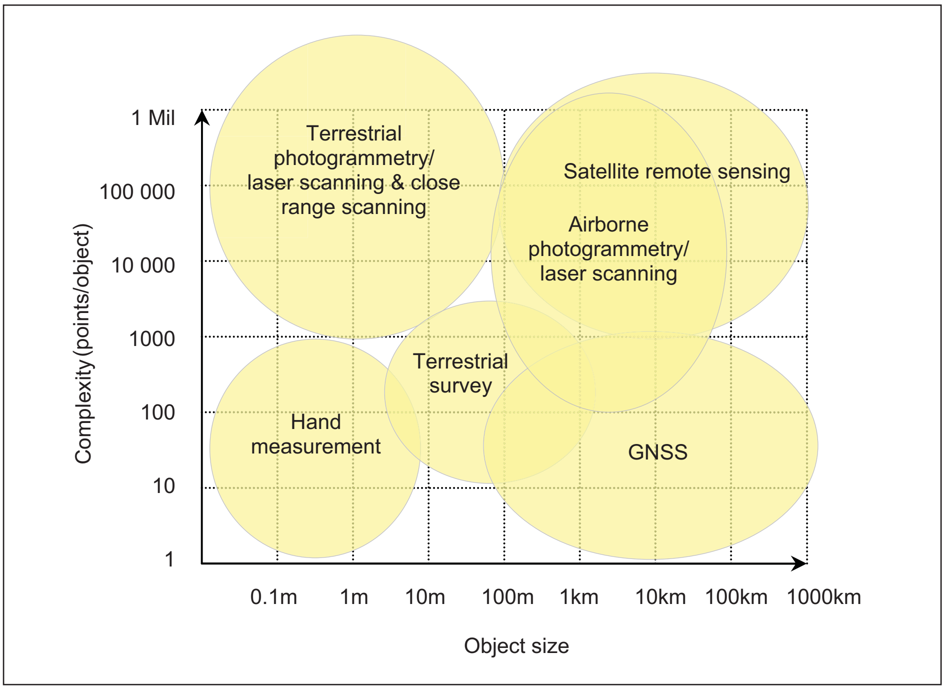


Fig 1 Three-dimensional survey techniques characterised by scale and object size (derived from Böhler presentation CIPA symposium 2001, Potsdam).

Fig 2 Triangulation laser scanning (courtesy of Conservation Technologies, National Museums Liverpool). **Fig 3** Time-of-flight laser scanning (courtesy of Wessex Archaeology).

This process might be undertaken from a static position or from a moving platform, such as an aircraft. Airborne laser scanning is frequently referred to as lidar (an acronym for 'light detection and ranging'), although lidar is a term that applies to a particular principle of operation, which includes laser scanners used from the ground. 'Laser scanning' is the preferred generic term and will be used throughout this guide to refer to ground based and airborne systems. For an in-depth guide to airborne laser scanning see the English Heritage publication, *The Light Fantastic – Using airborne lidar in archaeological survey* (Crutchley, S and Crow, P 2009).

Laser scanning from any platform generates a point cloud: a collection of XYZ co-ordinates in a common co-ordinate system that portrays to the viewer an understanding of the spatial distribution of a subject. For most laser scanning instruments, the point cloud can be regarded as the 'raw product' of a survey. The point cloud may also include additional information, such as return intensity or even colour values. Generally, a point cloud contains a relatively large number of co-ordinates in comparison with the volume the cloud occupies, rather than a few widely distributed points. Some instruments also provide more fundamental information on the full reflectance of the laser pulse (known as full-waveform scanners).

1.4 Questions laser scanning can help to answer

The key to deciding if you need to use laser scanning is thinking carefully about the questions you want to answer within your project. The questions asked will vary from discipline to discipline. Typical questions might be as simple as 'What does it look like?' or 'How big is it?' For example, a conservator might want to know how quickly a feature is changing, while an archaeologist might be interested in understanding how one feature in the landscape relates to another. An engineer might simply want to know the size of a structure and where existing services are located. In other terminology, laser scanning might help to inform on a particular subject by contributing to the understanding. Scanning may also improve the accessibility of the object, to aid expert understanding, or improve engagement with the general public.

Fig 4 Airborne laser scanning instrumentation (www.optech.ca/).

Once you have a clear idea of the questions you want to answer, then whether you need, or are able to use, laser scanning will depend on a range of variables and constraints.

1.5 Tasks appropriate for laser scanning

Laser scanning might have a use at any stage of a project. Tasks that might be considered as potentially suitable for the application of laser scanning could include any of the following:

- contributing to a record before renovation of a subject or site, which

would help in the design process as well as contribute to the archive record;
- contributing to a detailed record where a feature, structure or site might be lost or changed forever, such as in an archaeological excavation or for at a site at risk;
- structural or condition monitoring, such as looking at how the surface of an object changes over time in response to weather, pollution or vandalism;
- providing a digital geometric model of an object from which a replica can be generated for display, or as a replacement in a restoration scheme (*see* Case Study 6);
- contributing to three-dimensional models, animations and illustrations for presentation in visitor centres, museums, through the internet and through the media (enhancing accessibility/ engagement and helping to improve understanding);
- aiding the interpretation of archaeological features and their relationship across a landscape, thus contributing to understanding about the development of a site and its significance to the area;
- working, at a variety of scales, to uncover previously unnoticed archaeologically significant features – such as tool marks on an artefact – or looking at a landscape covered in vegetation or woodland (*see* Case Study 13);
- spatial analysis, not possible without three-dimensional data, such as line of sight or exaggeration of elevation.

It is important to recognise, however, that laser scanning is unlikely to be used in isolation to perform these tasks. It is highly recommended that photography should also be collected to provide a narrative record of the subject. In addition, on-site drawings, existing mapping and other survey measurements might also be required to aid interpretation and understanding.

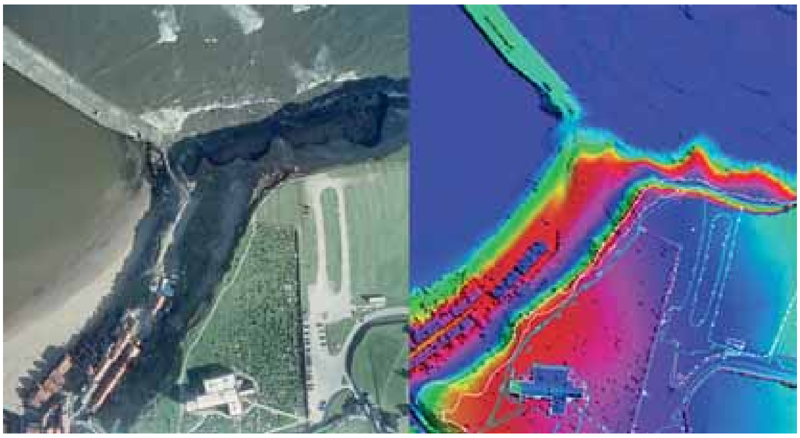


Fig 5 (left) An original and replica bust of the Emperor Caligula generated from data collected by a triangulation laser scanner (courtesy of Conservation Technologies, National Museums Liverpool).
Fig 6 (above) Laser scanning for historic sites at risk, St Mary's Church Whitby, North Yorkshire.

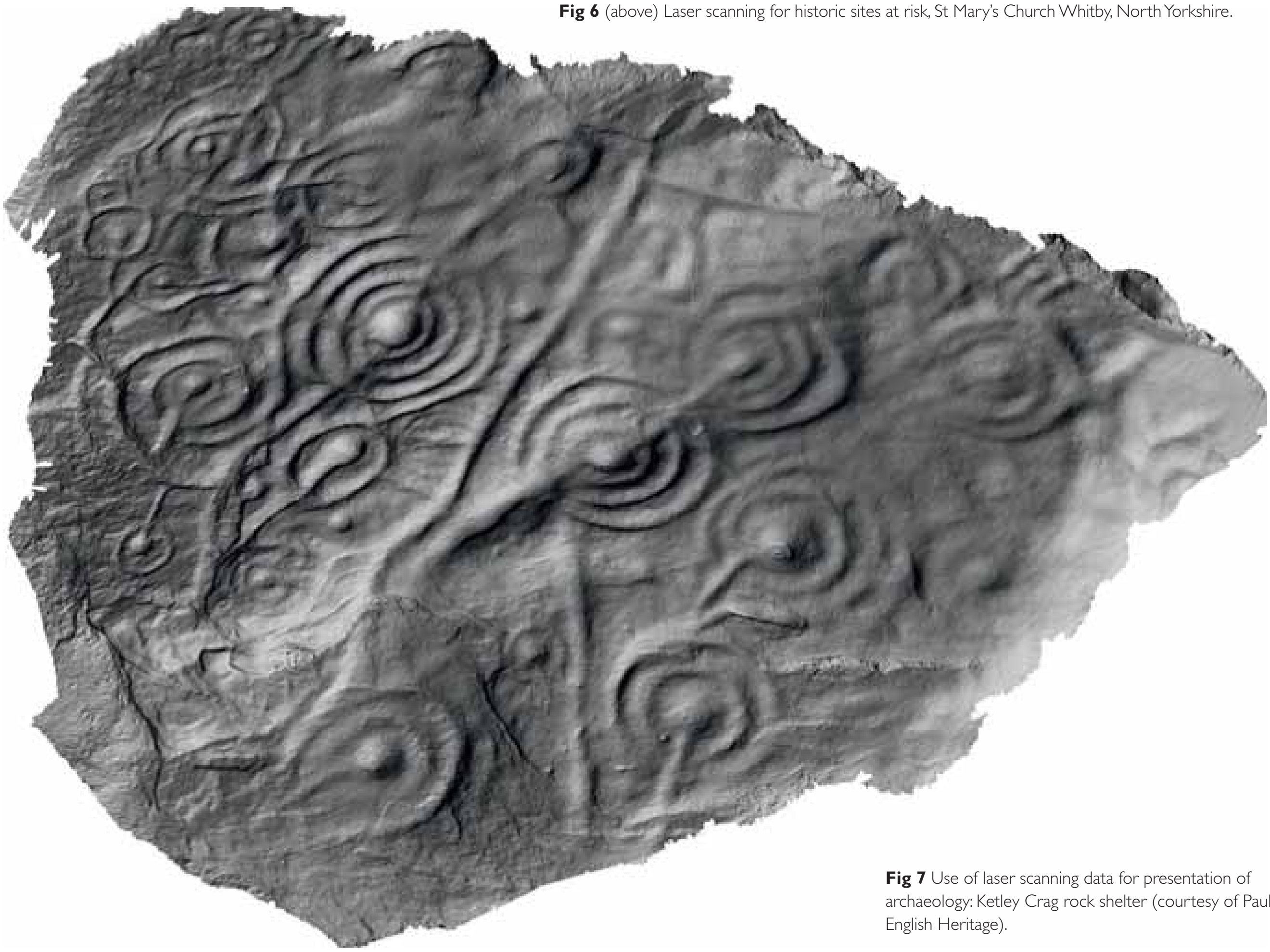


Fig 7 Use of laser scanning data for presentation of archaeology: Ketley Crag rock shelter (courtesy of Paul Bryan, English Heritage).

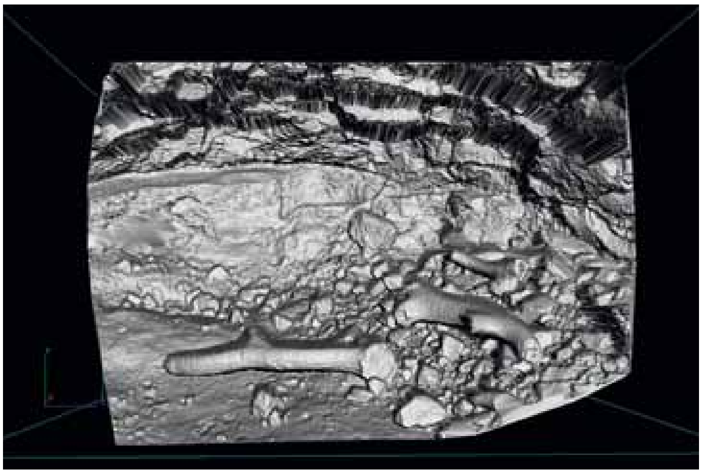
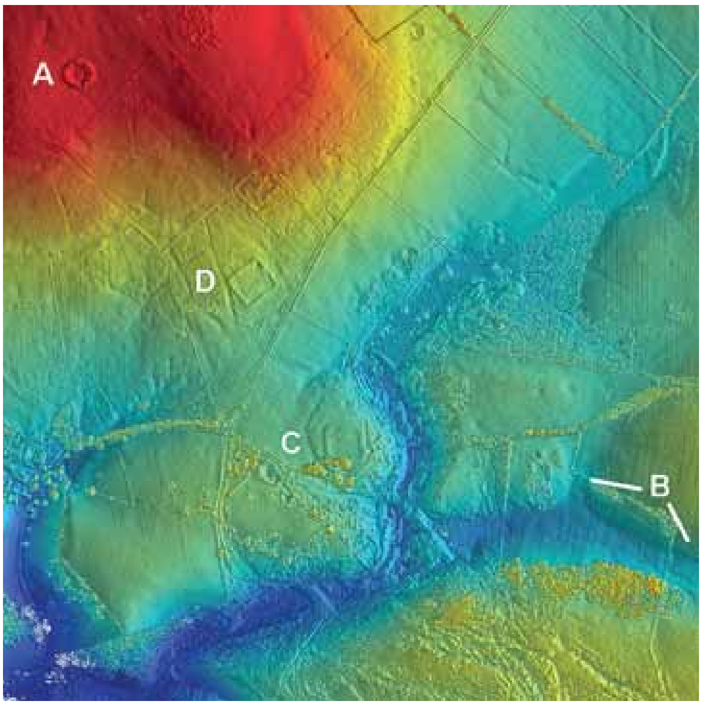
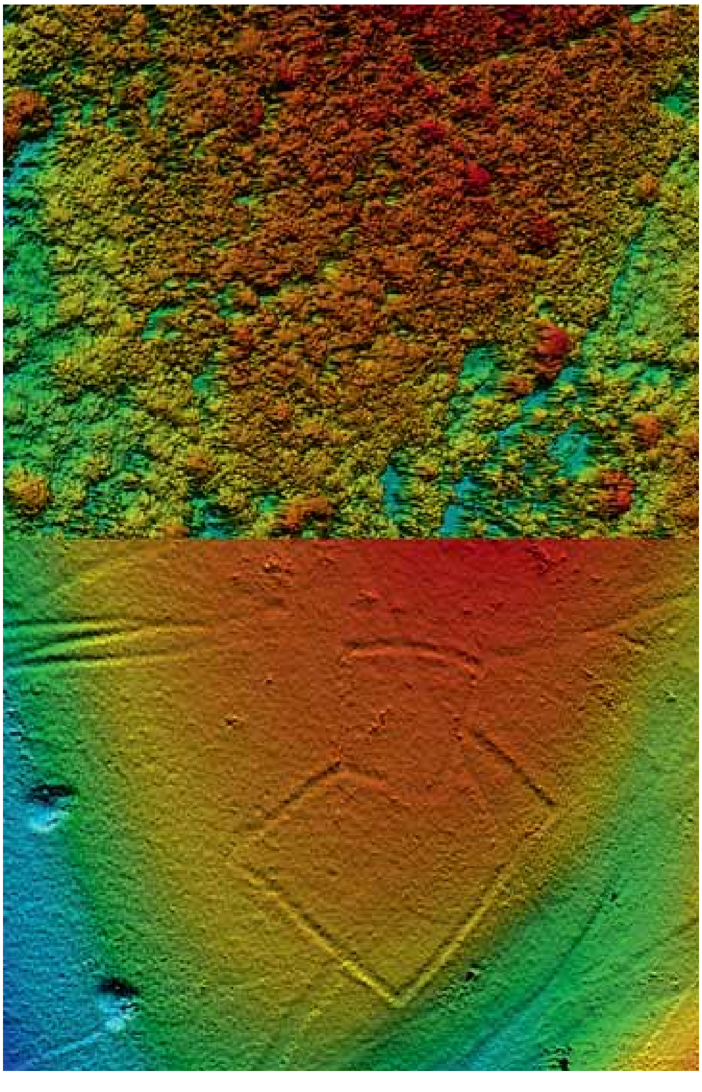


Fig 8 (above left) A profile of point cloud data used for a structural survey (courtesy of Tony Rogers, APR Services).
Fig 9 (left) Using laser scanning to contribute to a record during excavation (courtesy of the Discovery Programme Ltd).
Fig 10 (below left) Using airborne laser scanning to understand a historic landscape: an airborne laser-scanning image of the area around Charterhouse Roman town on the Mendip Hills. To the north-west is an amphitheatre (A), to the south-east are faint traces of the Roman road (B). In the bottom centre is the Roman fortlet (C), not to be confused with the sub-rectangular enclosure (D) of probable medieval or later date overlying the remains of the Roman town. The image is colour shaded according to height (ranging from red = high to blue = low); the height has been exaggerated to emphasise the features (courtesy of Mendip Hills AONB – Original source Unit for Landscape Modelling, Cambridge University).
Fig 11 (above) Laser scanning contributing to the site record of Grime's Graves Neolithic flint mine in Norfolk (courtesy of Paul Bryan, English Heritage).
Fig 12 (below) Looking at earthworks covered by vegetation (courtesy of Simon Crutchley, English Heritage and the Forestry Commission, data provided by Cambridge University Unit for Landscape Modelling).





1.6 What laser scanning cannot provide

Laser scanning will not provide a solution to all recording tasks. It does not provide unlimited geometric accuracy and completeness over objects and landscapes of all sizes at a low cost. In many cases, laser scanning might be considered unnecessary for the level of required deliverable output. Scanning, and in particular post-processing of the scan data, may also take a long time to achieve the level of results you require.

Laser scanners are not as versatile as cameras with regard to capturing data, as they require time to scan the object, whereas a camera can capture a scene almost instantaneously. Laser scanning requires line of sight to the object being recorded, meaning that it cannot see through objects (including dense vegetation), and it cannot see around corners. Scanning systems have minimum and maximum ranges over which they operate. Scanning above or below these ranges should be avoided so as to prevent inaccurate data capture. Some laser scanning equipment can have problems with reflectance from certain materials, such as marble or gilded surfaces. There are also health and safety factors to consider – see section 3.4.

While the point cloud generated by laser scanning may be useful as a product in its own right, it is more than likely that the point cloud will be a means to an end rather than the end itself. Laser scanning is best suited to the recording of surface information, rather than to edges and discrete points, although it is increasingly used to generate two-dimensional drawings in the form of elevations, sections, profiles and plans, particularly where supporting information, such as imagery, is also available.

Fig 13 Triangulation laser scanning of rock art, on site with a canopy to reduce the influence of bright sunlight (courtesy of Tertia Barnet)

2 How does laser scanning work?

2.1 Instrumentation and hardware

Obviously, particular tasks will have specific requirements. Generally, the larger the object the lower the accuracy and resolution that can be realistically achieved. Laser scanners operate on one of three ranging principles: triangulation, time of flight or phase comparison. Table 1 provides a short summary of these techniques, including typical system accuracy and typical operating ranges. The following paragraphs describe each technique in further detail.

Triangulation

Triangulation scanners calculate 3D co-ordinate measurements by triangulating the position of a spot or stripe of laser light. An outline schematic of a triangulation system is given in Fig 15. Some triangulation systems require an object to be placed on a moveable turntable that rotates the object

Table 1 Laser scanning techniques used in cultural heritage management activities

scanning system		*use*	*typical accuracy / operating range*
triangulation-based artefact scanners	rotation stage	• scanning small objects (that can be removed from site) • to produce data suitable for a replica of the object to be made	50 microns / 0.1m–1m
	arm mounted	• scanning small objects and small surfaces • can be performed on site if required • can be used to produce a replica	50 microns / 0.1m–1m
	mirror/prism	• scanning small object surface areas *in situ* • can be used to produce a replica	sub-mm / 0.1m–25m
terrestrial time-of-flight laser scanners		• to survey building façades and interiors, resulting in line drawings (with supporting data) and surface models	3–6mm at ranges up to several hundred metres
terrestrial phase-comparison laser scanners		• to survey building façades and interiors resulting in line drawings (with supporting data) and surface models – particularly where rapid data acquisition and high point density are required	*c* 5mm at ranges up to 50–100m
airborne laser scanning		• to map and prospect landscapes (including in forested areas)	0.05m+ (depending on the parameters of the survey) / 100m–3500m
mobile mapping		• to survey highways and railways • for city models • to monitor coastal erosion	10–50mm / 100–200m

(adapted from Barber, DM, Dallas, RWA and Mills, JP 2006 'Laser scanning for architectural conservation', *J Archit Conserv* **12**, 35–52)

Fig 14 A laser stripe from a triangulation scanner.

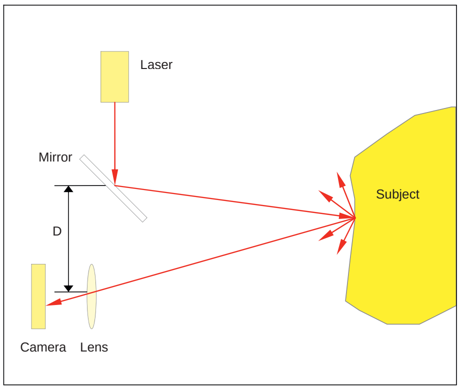


Fig 15 A schematic of a mirror-based triangulation measurement system. The laser generates a measurement beam that is deflected across the subject by a rotating mirror. The beam is then reflected by the surface of the subject and focussed onto the sensor by the lens. The location of the laser pulse on the sensor, plus the known separation (D) between it and the mirror is combined with the recorded angle of the mirror to determine a point co-ordinate by triangulation.

in front of a static scanner. Alternatively, systems may be mounted on a mechanical arm (Fig 2), which, while site portable, are more often found in specialist studios or laboratories. Typically, with this type of system, the scanner-to-object distance is less than 1m and commonly has a measurement accuracy of 0.1mm.

Although not providing the high level of accuracy associated with arm-based scanners, there are also triangulation systems that scan the measurement beam automatically, using mechanised prisms and mirrors. These systems can be likened to a tripod-based camera used to collect overlapping three-dimensional images of the subject at ranges of up to 2m. Such systems tend to be the most portable design, and are ideal for recording small architectural features such as detailed carvings or cut marks. Finally, some triangulation-based systems enable measurements at a range of up to 25m, although at this range you can expect a further degradation in accuracy. Triangulation scanners typically perform badly in bright sunlight, so temporary shading is often required (Fig 13).

Fig 16 (above) A time-of-flight laser scanner, showing measurement beam and direction of scan (courtesy of Riegl UK)
Fig 17 (below) A phase-comparison scanner (courtesy of Russel Geomatics).

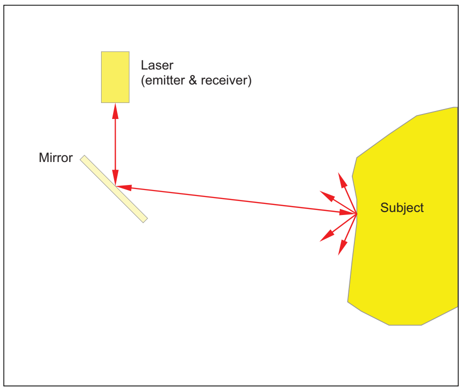


Fig 18 A schematic of a time-of-flight measurement system. The laser emitter generates a pulse and starts a timer. The rotating mirror deflects the beam, which strikes the subjects and is reflected. The reflected beam is returned to the receiving optics and the timer is stopped. This time (the known speed of light) and the recorded angle of the mirror are used to determine the XYZ co-ordinates.

Time of flight

Systems based on the measurement of the time of flight of a laser pulse and appropriate to architectural conservation activities typically offer a point accuracy of between 3mm and 6mm. Such systems use the two-way travel time of a pulse of laser energy to calculate a range. In comparison to triangulation systems, scanners using the time-of-flight method are more suited to general architectural recording tasks, owing to their longer ranges (typically between a minimum of 2m to a maximum of 300m). This type of scanner can be expected to collect many tens of thousands of points every minute by deflecting this laser pulse across the surface of an object, using a rotating mirror or prism.

Phase comparison

Phase-comparison systems, while offering similar accuracies to time-of-flight systems, calculate the range to the target slightly differently. A phase-comparison scanner bases its measurement of range on the differences in the signal between the emitted and returning laser pulses, rather than on the time of flight. Phase-comparison systems have much higher rates of data capture (millions of points per minute), which results in a much higher density of point cloud, but can lead to significant pressures on computer hardware in subsequent processing. While some time-of-flight and phase-comparison scanners are 'camera like' in that they have a field of view of approximately 40° × 40°, more typically such systems are now able to scan a full 360° in the horizontal and often 180° or more in the vertical.

Airborne laser scanning

Airborne laser scanners use laser scanning equipment based on time-of-flight or

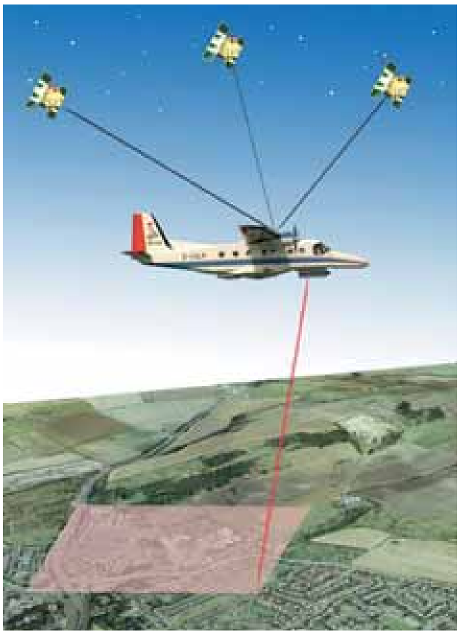


Fig 19 Airborne laser scanning.

phase-comparison principles. However, it is also necessary to couple the laser scanner with GNSS and inertial sensors to measure the position, orientation and attitude of the aircraft during data collection. By combining these measurements with the range data collected by the laser scanner a three-dimensional point cloud representing the topography of the land is produced, much like that generated from a ground-based static scanner.

Mobile mapping

Another recent technological development is in mobile mapping, which involves mounting one or more laser scanners and/or cameras on a vehicle in combination with direct positioning and orientation sensors. These systems are generally used for mapping highways or producing city models, although they have also been used in a variety of applications such as in the efficient surveying of beach and cliff profiles. As with airborne systems the movement of the vehicle, as recorded using GNSS and inertial sensors, as well as an accurate odometer, produces or contributes to the spacing of the measured points in one of the axes. Twin GNSS receivers separated by the length of the vehicle are often employed to accurately determine its heading. The inertial and odometer measurements are particularly important as the GNSS signal can easily become degraded in the urban environments where mobile mapping systems are typically employed. Apart from the obvious value of three-dimensional city models of historic areas, mobile mapping is currently of generally limited use for recording cultural heritage sites. Most historic sites are too delicate or restricted to allow access to the types of vehicles normally used for such systems. Also most applications require a greater level of accuracy and freedom from occlusion than most mobile mapping systems currently offer.

2.2 Software

Computer software is required at each stage of the laser scanning process. This includes the operation of the scanner, the processing of the collected data and the visualisation and utilisation of any delivered digital product. Operation of the scanner is likely to be handled by a contractor. Here the discussion is restricted to describing software for processing the collected data (also likely to be done by the contractor, but given here to provide an overview), and software that a user may need for viewing and using the final deliverables.

The choice of software will be based on a number of factors, including data quantity, the type of deliverable output required and user expertise and skill. The process of turning a point cloud into useful information is covered in section 5 below. However, it is useful to highlight here the significant components of software specially designed to be used with point cloud data. Such software will offer a three-dimensional viewer that can be used to preview the dataset. It will enable the view to be rotated, zoomed and panned, colours to be changed and data to be clipped from view. The software will have been designed specifically to handle large volumes of three-dimensional measurements. Mainstream software for CAD, GIS or 3D modelling was not originally designed to handle the large datasets now routinely generated by laser scanning. In some cases specialist point cloud processing engines can be obtained to improve the performance of these mainstream tools, making it possible to use a familiar software environment; also, many software providers are currently in the process of repackaging their software to meet the needs of laser scanning data.

A user who is commissioning a laser scanning survey is unlikely to need to consider exactly what software to use to process the collected data; rather, he or she will need to ensure that the methodology is appropriate for the needs of the project. The user will, however, need to ensure that the final product, generated from the point cloud, can be used for the task intended. It may be necessary to manipulate this within a standard desktop CAD or GIS package, or may require specialist software to enable easier visualisation and analysis. Free viewers designed for standard and proprietary formats are available, and low cost tools, designed to give a little more flexibility (such as the ability to make simple measurements), can be readily obtained. A good data provider should be able to provide a client with information on appropriate software to meet his or her needs. For more information on particular products, see section 7 Where to find out more.

2.3 Computer hardware

A standard desktop PC designed for general office use may be insufficiently powerful to take full advantage of the generated product, or for the proposed analysis. However, desktop PCs with computing power and specifications suitable for the day-to-day use of large geometric models (assuming appropriate software is installed) are now widely accessible and less expensive. Those planning to buy a new computer or upgrade an existing one in preparation for the use of three-dimensional data should refer to the minimum recommendations of individual software packages and consider the following points.

- 3D graphics acceleration: Having a dedicated 3D graphics card is one of the most important features. Note, some off-the-shelf machines provide 3D acceleration through integrated cards that share the computer's standard memory. Although less expensive this type of card should be avoided.
- RAM: The more the better. Memory is normally installed in pairs of modules, so when buying a new computer, consider what will be the most cost-effective way to add more memory in the future.
- Hard disk: Significant disk space will be required for day-to-day storage. Consider using an external hard disk to provide a local backup.
- Display: Do not underestimate the value of choosing a good quality monitor.
- Processor speed and type: While having a fast processor may improve general performance, it is less important than are graphics card and RAM.

If it seems expensive to buy a whole new system, an existing desktop PC might be upgradeable by the simple addition of extra RAM, a new graphics card and additional hard drives.

Do not forget that whatever software you choose to manipulate the derived models, you may also benefit from some training. Dedicated training helps to get you started on the right foot and stops you from adopting bad practices early on. Software developers, service providers or suitable educational establishments may all be able to provide appropriate training; for organisations that may be able to suggest suitable training partners, see section 7 Where to find out more.

3 Commissioning survey

3.1 Knowing what you want

It is unlikely that professionals in the heritage sector who require laser scanning data or products will themselves have the means or expertise to undertake the work. It is more likely that survey work will need to be commissioned and undertaken by a specialist contractor. The following tips will help when preparing to commission a survey.

- Consider the level of detail required and the extent of the subject. These are often the overriding parameters used to determine the appropriate survey technique and/or deliverable product.
- Start by working out what data are needed in order to answer the questions you have set. Try to come up with requirements for accuracy and products. It may not be necessary to specify the actual technique to be used, just the required products.
- Before you commission and procure the data, consider how you will use the product; additional costs might be hidden in buying new software/hardware.
- Discuss the requirements with possible contractors. A good contractor will be able to advise you if your requirements are achievable, realistic and necessary, as well as provide information on an alternative deliverable product that you may not have considered. Also discuss the work with other members of your organisation, especially with those with relevant expertise, as other uses for the survey data and products may be apparent to them, and may increase the overall value of the work to be commissioned.
- Consider how the collected survey will be archived and made available for use in the future. Take advice from national organisations such as the Archaeological Data Service (ADS) (*see* section 7.2 Organisations, for contact details). Determine who will own the collected data and the delivered product.
- Finally, prepare a project brief, using a standard document as a base, such as that published by English Heritage (eg Andrews, *et al* 2009 *Metric Survey Specifications for Cultural Heritage*).

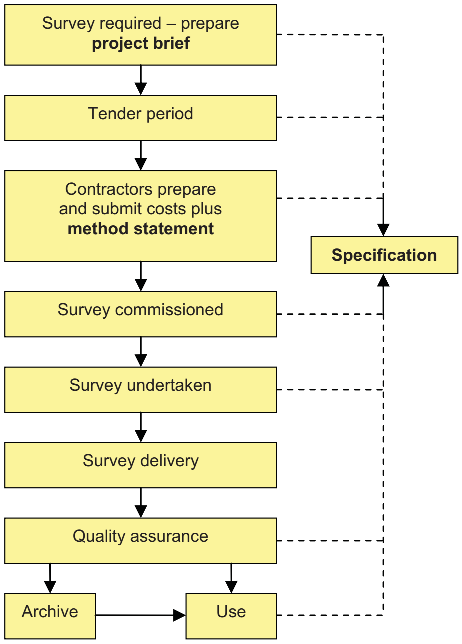


Fig 20 The survey flow line.

Those who are new to laser scanning may wish to carry out a small project first, before committing to a larger survey, in order to fully understand the benefits and limitations of the technique. Fig 20 shows a typical project flow line. After identifying the need for a survey to be undertaken, a project brief should be established by the client. The project brief should include information that helps the contractor understand the site-specific requirements of the survey. It should be written with direct reference to the survey specification, which should prompt the client for the relevant information. Once the project brief has been prepared, suitable contractors can be invited to tender. As well as a price, contractors should be asked to provide a method statement giving details of how they intend to undertake the survey. The survey can then be commissioned and the work undertaken.

During this work the contractor should follow their method statement, but will also need to refer to a standard specification for guidance where necessary. Upon completion the client will use the project brief and standard specification to undertake a quality assurance (QA) check before accepting the survey and passing it into the archive and on for use. Typically this is done through a visual inspection of the data to ensure that it shows what the user is expecting. In other cases this QA process might involve the comparison of the delivered survey against independent check points.

3.2 Determining appropriate point density

One of the key factors in commissioning a survey is being aware of what point density and measurement accuracy is required to generate the level of deliverable data required by the project. Generally, using a point density of less than the quoted measurement accuracy (for example, sampling every 1mm, when the measurement accuracy is 5mm) will not provide useful information. Based on standard mathematics used to determine appropriate minimum sampling intervals, and on the collection of a regular grid of data, a simple guide to appropriate point densities is given in Table 2.

When preparing to commission a survey, a user should be aware of the smallest sized feature he/she will require to be detected. This may not be the same over the entire subject, so it may be appropriate to employ different point densities in different areas of the survey. The scanner used should have a measurement precision of at least the point density of the scanning device used (for example, a laser scanner with a quoted precision of ±5mm should not be used to collect data at a point density of less than 5mm.)

3.3 Finding a contractor

Professional organisations, such as the Royal Institution of Chartered Surveyors (RICS) or trade organisations such as The Survey Association (TSA), will be able to help you to identify appropriate contractors. Alternatively, contact other individuals or other organisations with experience of commissioning projects and ask for recommendations.

Table 2 Appropriate point densities (sampling resolutions) for various sizes of cultural heritage feature

feature size	*example feature*	*point density required to give 66% probability that the feature will be visible*	*point density required to give a 95% probability that the feature will be visible*
10m	large earth work	3500mm	500mm
1m	small earth work/ditch	350mm	50mm
100mm	large stone masonry	35mm	5mm
10mm	flint galleting/large tool marks	3.5mm	0.5mm
1mm	weathered masonry	0.35mm	0.05mm

3.4 Laser safety

Laser light, in some cases, can be harmful. For example, some lasers used in survey applications may have risks associated with eye damage. To enable users to mitigate against any potential risk, all lasers are classified, according to the wavelength and the power of the energy that the laser produces. The International Electro-technical Commission (IEC) define applicable safety standards, known as IEC 60825 Standards, which have been adopted in Europe and are known as the EN 60825 Standard. Each European country has its own version of this standard; in Britain the standards document is known as BS EN 60825. The latest version of this, BS EN 60825-1:2007, Edition 2 – 'Safety of laser products – Part 1: Equipment classification and requirements' provides information on laser classes and precautions. It outlines seven classes of lasers (users should refer to the IEC Standards document to read the full safety information):

- Class 1 Lasers are safe under all conditions of normal use.
- Class 1M lasers are safe for all conditions of use except when passed through magnifying optics such as microscopes and telescopes.
- Class 2 lasers are safe because the blink reflex will limit the exposure to no more than 0.25 seconds.
- Class 2M lasers are also safe because of the blink reflex if not viewed through optical instruments.
- Class 3R lasers are considered safe if handled carefully, with restricted beam viewing.
- Class 3B lasers are hazardous if the eye is exposed directly, but diffuse reflections such as from paper or other matt surfaces are not harmful.
- Class 4 lasers can burn the skin, in addition to potentially devastating and permanent eye damage as a result of direct or diffuse beam viewing. This class of laser is not suited for survey applications.

Users of laser scanning systems should always be aware of the class of their instrument. In particular the user should ensure that the correct classification system is being used (note, for example, that the IEC 60825 standard is not adopted in the US). Particular precautions and procedures are outlined in the IEC standard for laser products used in surveying, alignment and levelling, and these standards should be followed by the contractor undertaking the scanning.

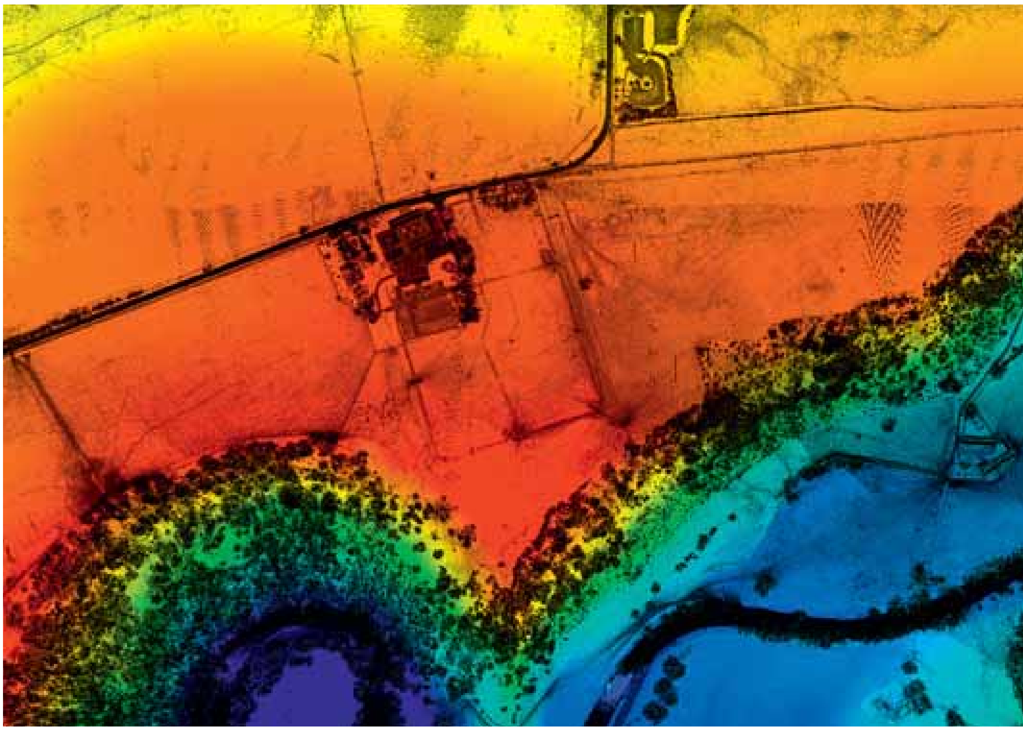


Fig 21 Elevation-shaded airborne laser scanning data for a rural area (blue: = low elevation; red = high elevation) (image courtesy of Newcastle University).

3.5 Archived data sources

In some cases you may be able to use archived data from commercial organisations or government agencies, especially for airborne laser scanning of landscapes and sites. However, be aware that these data may contain artefacts, owing to previous, less-sophisticated processing methods, which may be significant when performing analysis. Also note that the point density and measurement accuracy may not be sufficient for the analysis required.

4 From point cloud to useful information

4.1 Typical workflows

The commissioning of a survey is only the start of the survey process (*see* Fig 22 for a general schematic with examples of deliverable data). In order to turn scan data into a useful product the scans must first be registered, generally through the use of additional survey measurements, to provide some control. This will be undertaken by the contractor, who will then, most

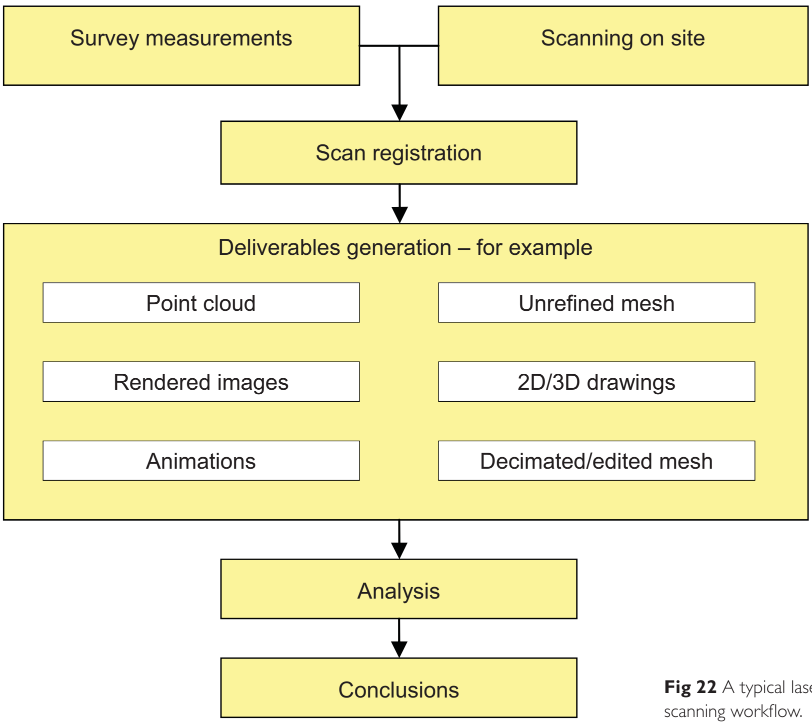


Fig 22 A typical laser scanning workflow.

likely, generate some defined deliverable output. At this stage the user who has commissioned or procured the survey will want to undertake some form of analysis to help answer the questions that were originally posed.

4.2 Cloud alignment or registration

For anything other than the simplest planar object, a number of separate scans from different locations are usually required to ensure full coverage of the object, structure or site. When collected, individual scans are most likely to be based on an arbitrary co-ordinate system, so in order to use several scans together their position and orientation must be changed so that each scan uses a common co-ordinate system (this may be based on a local site grid).

This process is known as cloud alignment, or registration. For example, scan one and scan two in Figs 23 and 24 are initially in separate reference systems and cannot be used together until they have undergone a registration process, as shown in Fig 25. If the collected data need to be referenced to a real world co-ordinate system, then it will be necessary to provide additional survey measurements. In the case of airborne laser scanning this is accomplished directly through the use of positioning and orientation observations on-board the aircraft; however, best practice still involves the collection of some ground control to provide redundancy and check observations. When using an arm-mounted triangulation laser scanner, all co-ordinate measurements are collected in a known system, so registration may not be required.

4.3 Modelling

The general term for the process required to turn the collected point cloud information into a more useful product is modelling, or more specifically, surface or geometric modelling. There are a number of different approaches to modelling that can be used to turn the point cloud into useful information. For a small artefact, or for any object scanned with a high accuracy triangulation scanner, the most typical product would be a digital model of the object's geometry, probably in the form of a meshed surface, such as a triangular irregular network (TIN). Figs 26 and 27 show a point cloud before and

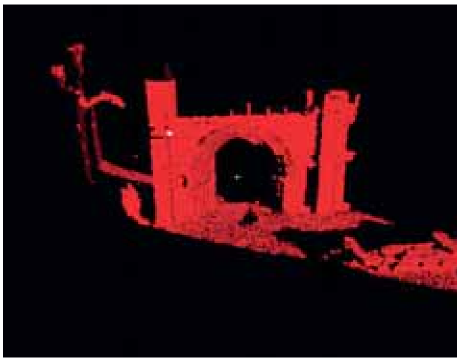


Fig 23 Scan one of the doorway.

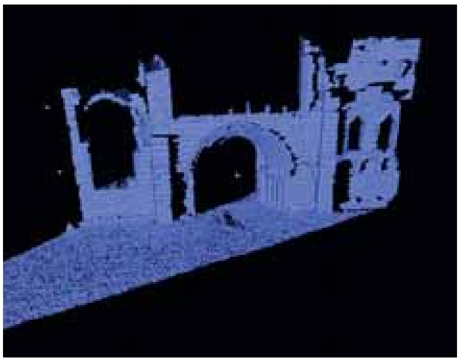


Fig 24 Scan two of the doorway.

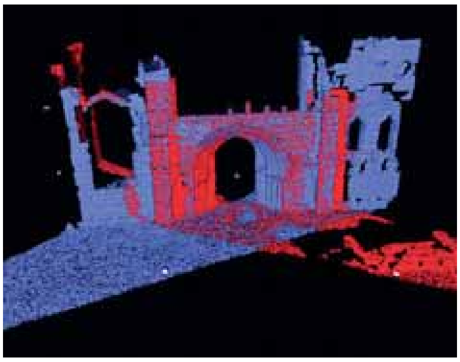


Fig 25 The scans of the doorway registered onto the same co-ordinate system.

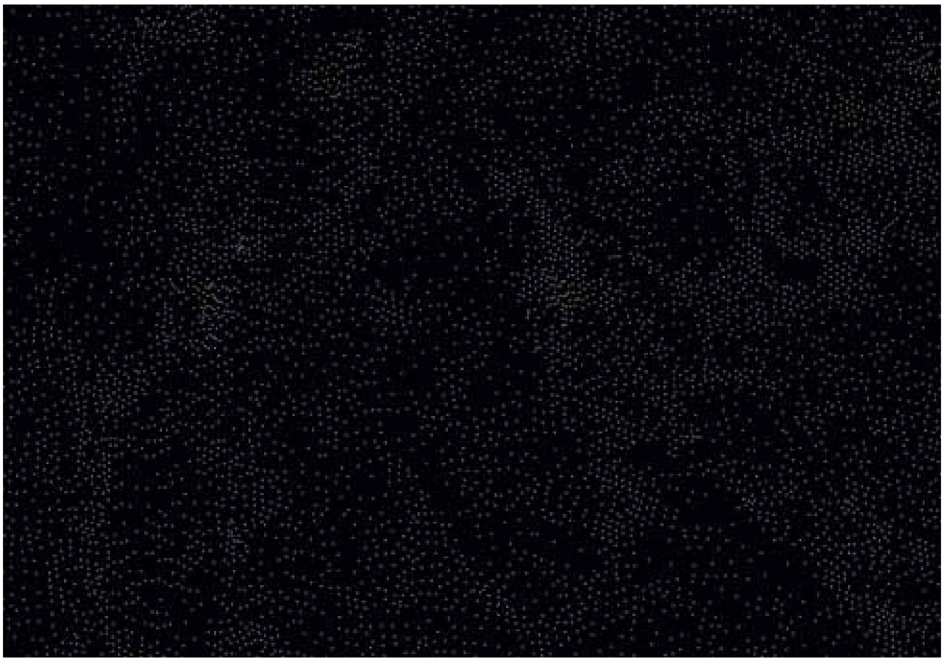


Fig 26 An unorganised point cloud before meshing, showing a portion of the Upton Bishop fragment (courtesy of Conservation Technologies, National Museums Liverpool).

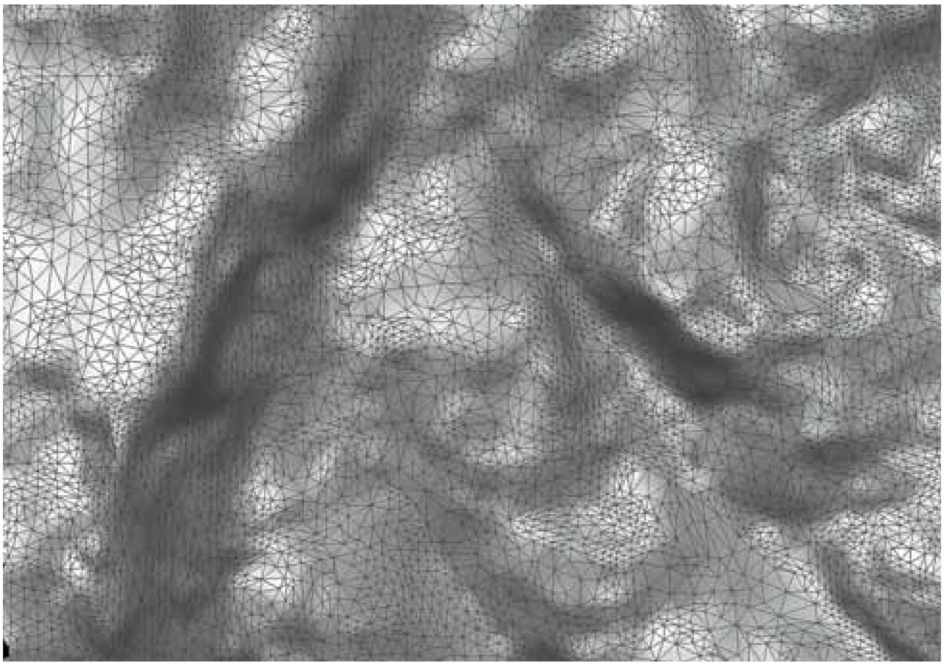


Fig 27 A meshed point cloud showing a portion of the Upton Bishop fragment (courtesy of Conservation Technologies, National Museums Liverpool).

Fig 28 An original stone fragment (top) and a reconstructed geometric model (bottom) from laser scanning data (courtesy of Conservation Technologies, National Museums Liverpool).

after meshing, to form a TIN. In order to generate a complete, continuous model of the subject it is likely that some editing of the TIN will be required to fill holes where no data were collected. The resulting TIN is suitable for use in several types of analysis. Fig 28 shows the result of meshing point data collected by laser scanning.

The options for processing in a ground-based system are typically more varied. While a meshed model might be required, plans, profiles, sections and elevations (line drawings) could be generated by using the point cloud as a base from which features are traced, based on the edges in the geometry and intensity data (Fig 29). However, this is still not a fully automatic process and requires skill and experience on the part of the users. The resulting drawing, without the underlying point cloud, will be a fraction of the file size of the original dataset.

With airborne laser scanning the most typical product is a digital terrain model (DTM). The first task in producing a DTM is to undertake a classification of the available points in order to separate the ground points from surface features such as houses and vegetation. Using semi-automated algorithms the points that represent the ground can be identified. The ground surface can be used as a reference to classify other points as 'vegetation' and 'structure' classes. The ground points can then be used to generate a DTM, interpolating where necessary underneath buildings and vegetation. The DTM will initially be in the form of a TIN, where the surface is formed by a series of interconnecting triangles.

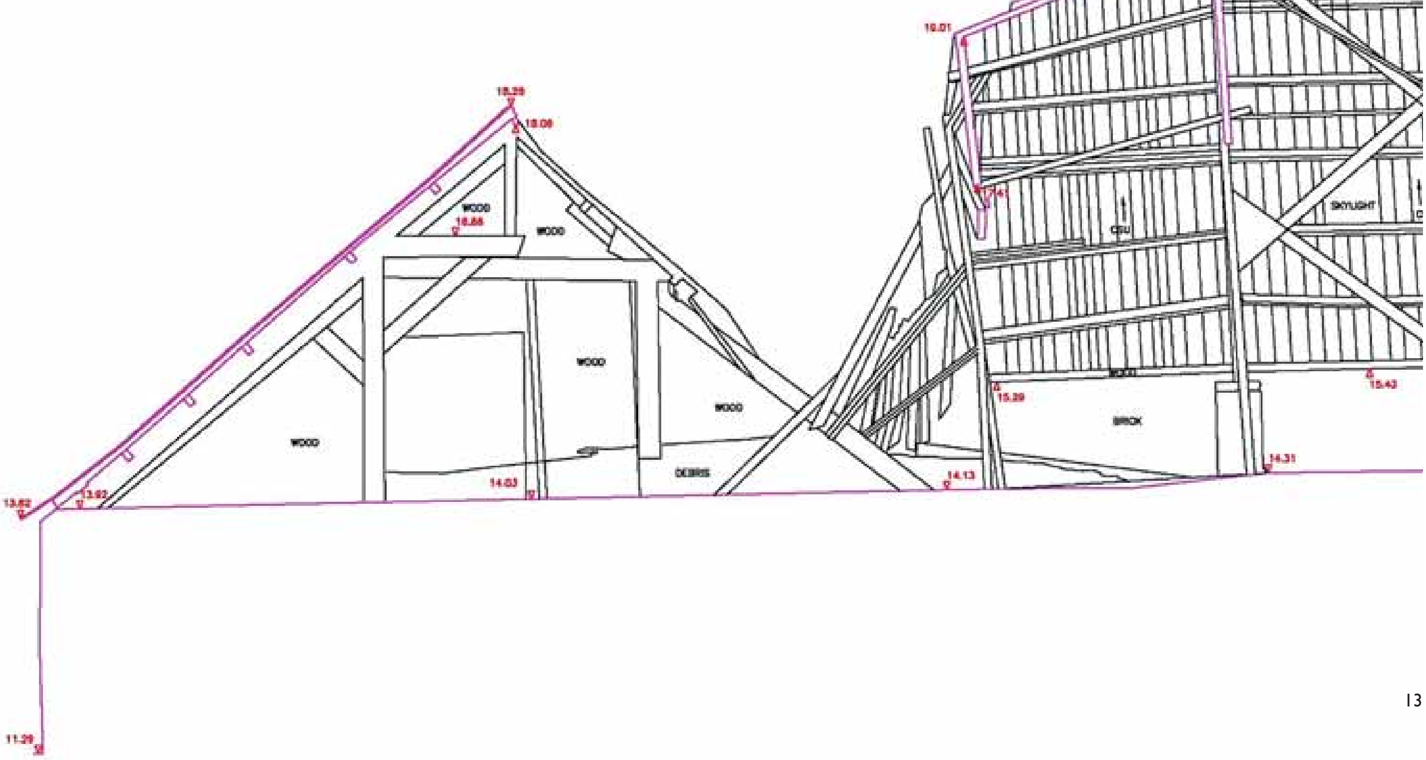


Fig 29 A drawing generated from laser scanning data and narrative imagery (courtesy of Tony Rogers, APR Services).

Fig 30 A triangulated model of rock carvings with artificial raking light (courtesy of Paul Bryan, English Heritage).

This TIN can also be used to create an interpolated grid, in which each element in the grid represents terrain surface elevation. A grid-based DTM might be more suitable for using within a mainstream GIS (Fig 10 is an example).

4.4 Analysis

The delivery of a product derived from laser scanning data is only the start of the process of answering the original research questions. Some form of analysis is likely to be required using the final product. In fact, some of this analysis may be best done during the processing stage itself; therefore, consider talking to or working with the contractor during the initial post-processing. Analysis, during or after the generation of deliverable data, should always include supplementary data to support any conclusions made. Consider how supplementary datasets (such as historic mapping, or photos used within a GIS) might help (*see* Case Study 13).

As laser scanning provides three-dimensional data it lends itself well to three-dimensional queries. Line-of-sight analysis allows a user to quantify if one part of the model can be seen from another location. For example, could a monument be seen from the valley floor? This procedure is frequently used in the analysis of a landscape.

Another useful technique for analysing a surface is to use artificial raking light to illuminate a scene from directions not possible if relying on sunlight alone (Fig 30; *see also* Case Study 10).

Subtle features might also be identified using vertical exaggeration. By exaggerating the vertical scale at which features are displayed, slight variations in topography are often revealed. This may be coupled with the use of artificial raking light.

Neither of these analysis techniques would be possible without detailed three-dimensional information, to which laser scanning has greatly improved access. While laser scanning explicitly provides geometry, most time-of-flight laser scanners also provide a value that indicates the strength of the returning laser signal. This intensity data can be useful as an additional information source during analysis, for example in the identification of different stratigraphy in a laser scan of exposed soil. As most scanners operate outside of the spectrum visible to the human eye the intensity information collected is often slightly different to that seen in the field. Such information can be useful, in some cases, in differentiating between slight changes in surface or material type. Fig 32 shows an example of how the intensity information from a scan of an archaeological excavation can be compared with the record made on site. However, care must be taken when using such information for anything more than qualitative interpretation, as quantitative use may necessitate careful calibration of the intensity values.

Three-dimensional geometric models can also be used to generate high-quality still or animated scenes. Movies are often successfully used to present what would otherwise be large quantities of data requiring specialist viewing software and hardware. While such presentation does not provide an environment through which a user can navigate freely, it does serve a useful purpose in presenting an object, site or landscape to a non-specialist group. Such models generally include the use of image

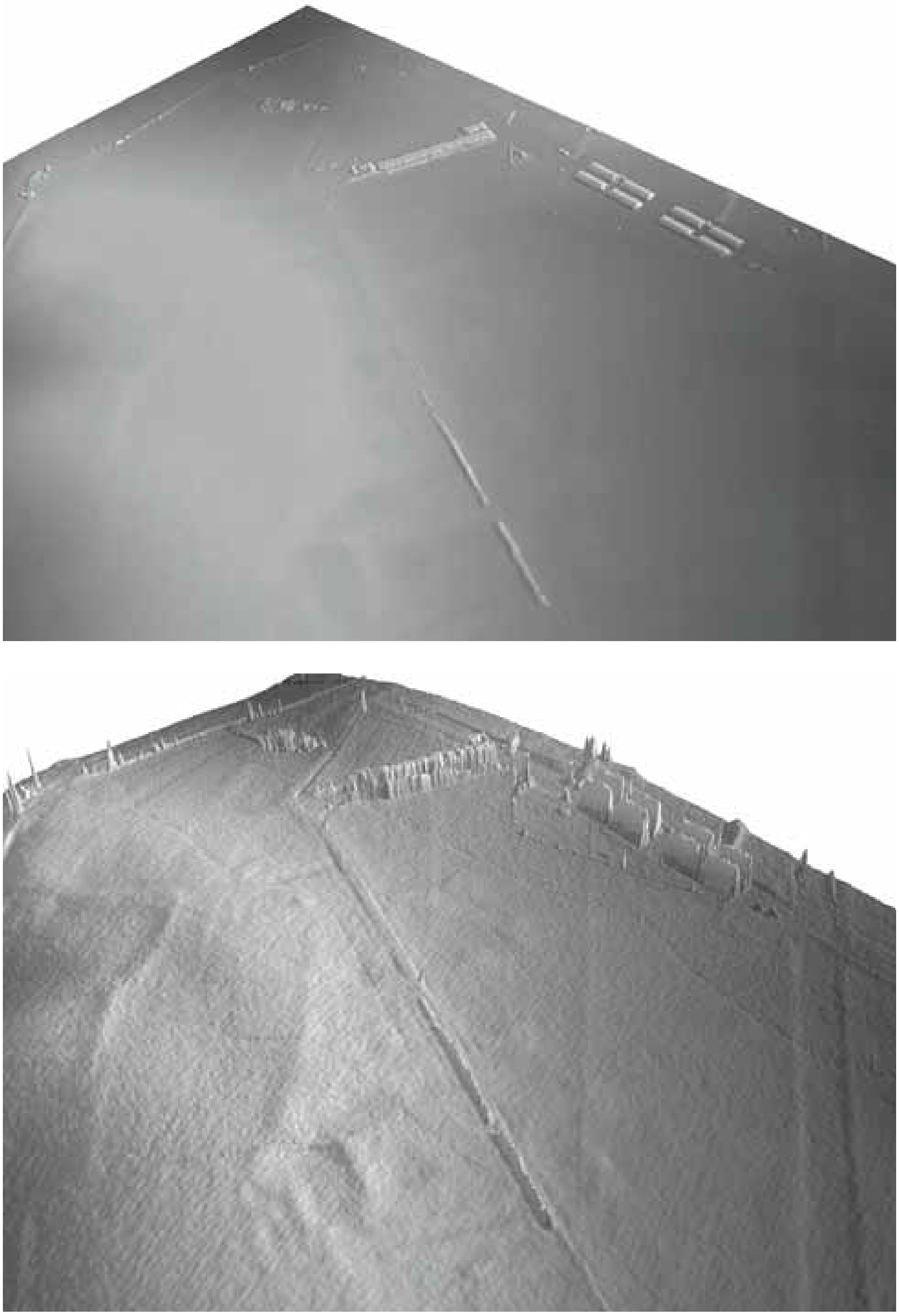
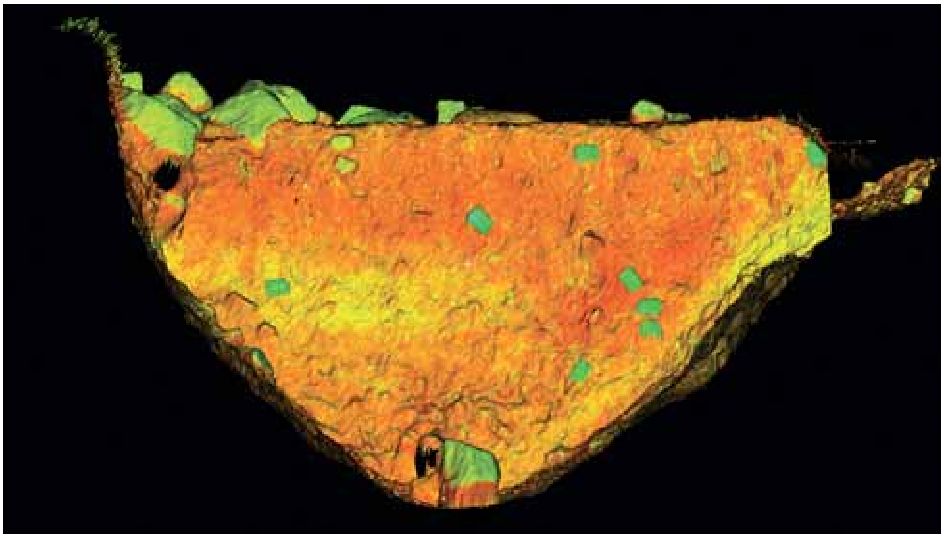


Fig 31 Elevation data from airborne laser scanning in the Witham Valley (top) and displayed with ten-fold vertical exaggeration (bottom), revealing possible early field systems to the left of the image (courtesy of Simon Crutchley, English Heritage, data courtesy of Lincolnshire County Council – Source Environment Agency).



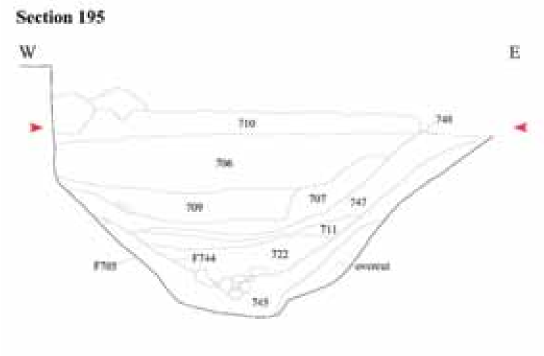


Fig 32 A laser scan of an excavated section with intensity information (left), and a stratigraphic record of the ditch made by an archaeologist on site (above) (courtesy of Newcastle University and University of Durham).

textures. This textural information can often help to replicate geometric detail, and reduce the need for some vertices (*see* Case Study 1).

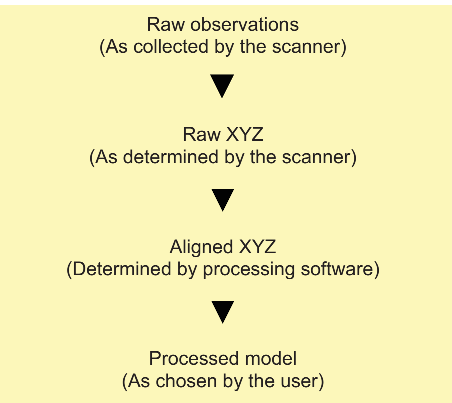
A number of laser scanner manufacturers now offer software that enables the point cloud data, or a proxy of it, to be served over the internet. In most cases only the immediately visible data are actually downloaded. So this enables the non-specialist user to view and interrogate the data without the need for significant investment in computer hardware or software, although such a user may have to install a plug-in for their web browser. The data provider may, of course, need to pass on the web hosting costs to the client or in some cases the same software can be used to view data supplied on DVD or on an external hard disk.

5 Managing data

5.1 Reprocessing data

Various different data types are generated at a number of stages during a laser scanning survey. In order to be able to reprocess these data at a later date, a user should ensure that the appropriate types are still available. Fig 33 summarises these stages and the data they produce.

Fig 33 Types of data arising from laser scanning.



Raw observations (angles and distances) are not universally available, and data formats differ between manufacturers. Raw XYZ co-ordinates are, instead, the most preferred data source for reprocessing, which could include tasks such as realignment of scans. Whatever data you have, you should also ensure that you have a record of the processing history, including information on any down-sampling of point cloud density (often referred to as 'decimation' when used in reference to data manipulation).

If you want to ensure that data can be used in the future, it is recommended that service providers should retain the proprietary observations after completion of the survey for a minimum of six years. This should include: field notes and/or diagrams generated while on site; the raw and processed data used for the final computation of co-ordinate and level values; and a working digital copy of the metric survey data that form each survey.

5.2 Data formats and archiving

Data exchange formats are used to make the transfer of data between users easier. Proprietary formats should be avoided for this reason. A simple text file (often referred to as ASCII) providing fields for XYZ co-ordinates, intensity information and possibly colour (RGB) information would generally be sufficient for the transfer of raw data between one software package and the next. However, in order to standardise the transfer of such information, and ensure that important information is not lost in transition, it might be appropriate to consider a formal data exchange format. An emerging transfer format for point cloud data is the LAS format, overseen by the American Society for Photogrammetry and Remote Sensing (ASPRS). This open source format was originally developed for the transfer of airborne laser scanning between contractors and software packages, but it can also be used to transfer ground-based laser scanning data.

Of perhaps more concern to the end user are the formats chosen to deliver the actual product to be used. Obviously the format needs to be compatible with the tools that you intend to use. An example general purpose format for the delivery of meshed models is the Alias Wavefront OBJ format. The type of deliverable product will dictate the range of data formats that can be used. For typical raw and interpreted scan data the following delivery formats should be considered:

- digital terrain models (DTM): any text based grid format
- TIN models: Wavefront OBJ
- CAD drawings: DXF, DWG
- movies/animations: QuickTime MOV, Windows AVI
- rendered images: TIFF, JPG
- replication: STL

The deliverable product may also include written reports, which should generally be delivered in PDF format for dissemination, and with an ASCII text file version also provided for archiving.

For detailed guidelines on issues of archiving, including appropriate file formats, readers should refer to the Archaeological Data Service (ADS) 'Big Data' project.

5.3 Metadata

An important component of the data management process is the definition and management of metadata, ie data about the data. This is especially true when submitting the final record to archiving organisations such as the ADS. The very minimum level of information that should be maintained for raw scan data will include the following:

- file name of the raw data
- date of capture
- scanning system used (with manufacturer's serial number)
- company name
- monument name
- monument number (if known)
- project reference number (if known)
- scan number (unique scan number for this survey)
- total number of points
- point density on the object (with reference range)
- weather conditions during scanning (outdoor scanning only)

For full details of the metadata required by English Heritage, see *Metric Survey Specifications for Cultural Heritage* (Andrews, *et al* 2009).

6 Helping you to decide

Asking the following questions will help you to better understand what your requirements are and whether laser scanning, in its various forms, is suitable. It will also help to identify possible alternatives.

6.1 What outputs are wanted?

Scanning can contribute to a whole range of outputs, so deciding what outputs you require will help to determine an appropriate project brief. Outputs might include a highly edited surface mesh, two-dimensional drawings, rendered movies or even virtual environments. Other forms of data, such as images and survey control, are likely to be required to contribute to these outputs.

The scale of your output is a key decision, which will help determine the accuracy of the product and the required point density. Next, think about how you will use the output. Does it need to be hard copy, perhaps for annotation on site? Do you need to be able to edit it yourself, view it as part of some interpretation activity, or will it simply be used for dissemination and reporting, for example as part of a presentation? If there are other potential users of the output, for example within a project team, consider what sort of output they might require.

6.2 How big is the subject?

The size of the object or site in question helps to define the type of laser scanning that it would be appropriate to apply. A triangulation laser scanner can provide measurements to an accuracy of less than 1mm and point densities of around the same scale, so would be ideal for the recording of a small artefact or statue. A feature on a building, albeit larger, might also be suitable for measurement using a triangulation scanner, although if the object is fixed in place, access to it will require consideration. Alternatively, it might be suitable to use a system based on time-of-flight or phase-comparison measurement.

At the scale of a building façade or of an entire building, measured survey using triangulation scanners would most likely take an unjustifiably long time and would provide data at far too high a resolution (in addition to being very expensive). Therefore, given their suitability for larger objects, owing to their greater working range, a time-of-flight or phase-comparison scanner would be more appropriate.

For entire sites, where topography is of interest, time-of-flight scanning, using a scanner with a 360-degree field of view would be feasible, whereas for an entire landscape, incorporating a number of sites of interest, airborne survey would probably be the only feasible solution.

6.3 What level of accuracy is required?

This is typically related to object size and the purpose of the survey. A common answer is 'the best that you can do', but this is not always helpful in deciding what type of technique should be used. It is perhaps more correct to ask what is the optimum accuracy that balances the needs of the task, the capability of the technique and the budget available.

6.4 What resolution of measurement?

Again, this is typically related to object size and the purpose of survey. Resolution is the density of co-ordinate measurements over the subject area. With a subject that has a complex shape or sharp edges, it is necessary to have high-resolution measurements so that the resulting data have a high fidelity to the original subject. There might be situations where the best option is to combine a number of resolutions: low-point density in areas of reduced complexity, or where high levels of detail are not required, along with higher resolution areas of high complexity and interest. For example, the recording of a building façade may require very high-resolution measurements of detailed carvings such as tympana while, in comparison, the rest of the building requires a basic record of dimensions and layout. The choice of resolution should also be balanced against the accuracy of the system measurements.

6.5 Does the survey need to be geo-referenced?

When working on structures, buildings, sites and landscapes it is likely that the data will need to be linked to a local or national reference system. This makes it possible to use the collected data alongside other spatial datasets on the same system. It is less likely that a small object or feature will need to be referenced to a common system, although its original spatial location and orientation might need to be recorded.

6.6 Time and access restrictions?

Access and time might be unlimited. For example, the object might be brought to a studio-based scanner. Alternatively, access to the subject may be easy, perhaps because temporary scaffolding is in place, but time may be restricted because the scaffolding will be dismantled, making future access impossible unless new scaffolding is erected. Note that while scanning from a static position requires a stable platform, scanning from scaffolding or from a mast or hydraulic platform is possible, although care should be taken to ensure that the scanner remains stable during operation (Fig 34).

Access might be restricted on health and safety grounds, because a building is unsafe, making a survey possible only from a few locations (*see* Case Study 1). In an archaeological excavation, survey may

Fig 34 Laser scanning from an extra tall tripod (courtesy of Nick Russill, TerraDat).

be time-critical, as recording is required at each part of the excavation and cannot be repeated. This requires scanning to be available on site during excavation.

The weather can also impose limitations. Scanning in heavy rain is generally unsuitable, as rain on the scan window can refract the measurement beam. Airborne survey is, to some extent, also restricted by weather. Survey might also be required at a particular time, for example if data collection is required when trees are in leaf or when bare (in surveying terminology 'leaf on' or 'leaf off' conditions).

6.7 Is three-dimensional information required?

If yes, consider how the information is going to be used. This will help you or the contractor to determine the processing that will be required on the laser scanning data. Even if the answer is no, and you only need two-dimensional measurements and dimensions, laser scanning may still be useful. Laser scanning can be used to provide line drawings in elevation, section, and plan. It is especially useful when access to a site makes it difficult to use conventional methods. The way in which laser scanning enables direct integration of the collected data on site can also help a contractor to reduce the likelihood of revisits.

6.8 Budget

Although laser scanning is still generally regarded as a high-cost technique, it can be justified, as the information required may not be available in any other way. If the budget is limited, or non-existent, laser scanning probably is not a technique that you can use. Where it is adopted, it is advisable to try to ensure that it can be used in many different ways, so as to provide best value from its commissioning. A number of measured building survey contractors have found that laser scanning is a cost-effective route to producing plans and elevations due to the reduced time on site as compared with conventional survey methods. For a large organisation the savings could fairly quickly compensate for the high initial capital outlay.

6.9 Can you do this yourself?

It may be possible to undertake the data collection and data processing yourself. However, scanning requires specialist skills in order to achieve a precise and reliable product. This might include techniques for providing precise survey control measurement and/or knowledge of 3D CAD or GIS software. If this is your first project, using a contractor is advisable.

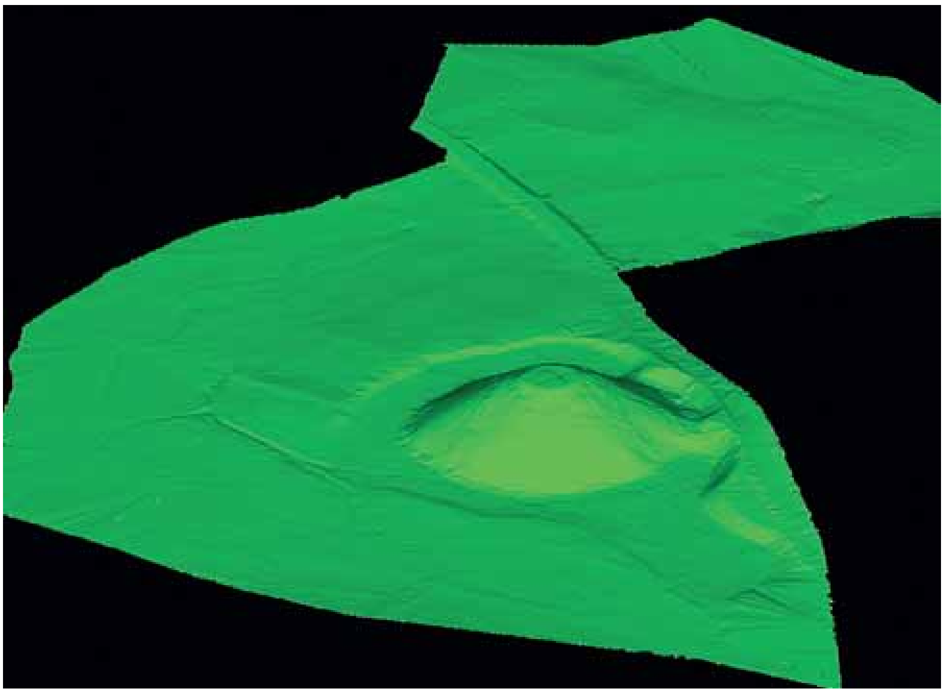
Fig 35 An operator using a digital photogrammetric workstation (courtesy of English Heritage).

6.10 What are the alternatives?

Digital photogrammetry (Fig 35) is the technique to which laser scanning is most often compared. Photogrammetry is increasingly accessible today, compared with a decade or more ago when it generally required the use of specialist analytical instruments. It can provide a highly scalable and accurate method of measuring surface topography. It can also be used from the air, or from the ground, although as a non-active measurement technique (photographs only record the light reflected from the sun or other illumination source) it is less able to measure through small gaps in forest canopies. Thus, where a site is covered in woodland, laser scanning may be the only solution that can provide measurement to the forest floor.

A terrestrial, topographic survey using differential GNSS (Fig 36) or a total station survey may provide a lower-cost site plan, but over a large landscape this might not be suitable. Total station survey using reflectorless EDM measurement can also be used to generate building façade elevations, in real time or using post-processing in CAD. Hand recording using tape and plumb line can provide accurate records of small features, objects or structures.

Fig 36 A digital terrain model generated by ground based GNSS survey (courtesy of English Heritage).



7 Where to find out more

7.1 Charters and guidance

The aims of recording within the scope of conservation and restoration are provided in the Venice Charter, drawn up in May 1964 (www.international.icomos.org/e_venice.htm).

Overall guidance and a detailed specification for the use of recording techniques are found in Andrews, D (ed) *et al* 2009 *Metric Survey Specifications for Cultural Heritage Swindon*. Swindon: English Heritage (available for purchase or as a free to download, PDF file from the English Heritage website).

7.2 Organisations

There are a number of organisations whose members have expertise in laser scanning and in the provision of three-dimensional survey. They may be able to help you find an appropriate contractor, or be willing to talk over your particular needs.

The Archaeology Data Service
Department of Archaeology
University of York
King's Manor
Exhibition Square
York YO1 7EP
ads.ahds.ac.uk/

English Heritage
37 Tanner Row
English Heritage
York YO1 6WP
www.english-heritage.org.uk/professional/research/heritage-science/specialist-survey-techniques

Remote Sensing and Photogrammetry Society (Laser Scanning and Lidar Special Interest Group)
c/o Department of Geography
The University of Nottingham
University Park
Nottingham NG7 2RD
United Kingdom
www.rspsoc.org/

Royal Institute of Charted Surveyors (RICS) Mapping and Positioning Practice Panel
12 Great George Street
Parliament Square
London SW1P 3AD
United Kingdom
www.rics.org/

Chartered Institution of Civil Engineering Surveyors
Dominion House
Sibson Road
Sale
Cheshire M33 7PP
United Kingdom
www.cices.org

The Survey Association
Northgate Business Centre
38 Northgate
Newark-on-Trent
Notts NG24 1EZ
United Kingdom
www.tsa-uk.org.uk/

7.3 Books

To date, there are no books that exclusively cover the use of laser scanning in cultural heritage. However, there are some useful guides to the needs and methods of measured survey in cultural heritage and a number of others about terrestrial laser scanning.

Andrews, D *et al* 2010 *Measured and Drawn : Techniques and Practice for the Metric Survey of Historic Buildings* (2 edn). Swindon: English Heritage

Crutchley, S and Crow, P 2009 *The Light Fantastic: Using Airborne Lidar in Archaeological Survey*. Swindon: English Heritage

Dallas, R W A 2003 *A Guide for Practitioners: Measured Survey and Building Recording*. Edinburgh: Historic Scotland

Heritage, G and Large, A 2009 *Laser Scanning for the Environmental Sciences*. Chichester: Wiley Blackwell

Shan, J and Toth, C 2009 *Topographic Laser Ranging and Scanning: Principles and Processing*. Boca Raton, FL: Taylor and Francis

Vosselman, V and Maas, H-G 2010 *Airborne and Terrestrial Laser Scanning*. Dunbeath: Whittles Publishing

7.4 Journals and conference proceedings

There is no specific journal for laser scanning, but many major academic journals that cover survey techniques and cultural heritage routinely include papers on the subject:

ISPRS Journal of Photogrammetry and Remote Sensing (Amsterdam: Elsevier)

The Photogrammetric Record (Oxford: Wiley Blackwell)

Journal of Architectural Conservation (Shaftesbury: Donhead)

There is also a range of professional journals that often provide annual software and hardware reviews on laser scanning:

Geomatics World (PV Publications, UK)
Engineering Surveying Showcase (PV Publications, UK)
Civil Engineering Surveyor (CICES, UK)
GIM International (Geomares Publishing, Netherlands)

There are also a number of regular conferences where research on, and the application of, laser scanning is presented, and that publish comprehensive proceedings:

Symposia for the International Committee for Architectural Photogrammetry (CIPA). Held every two years, the proceedings of this symposia can be found online at: www. cipa.icomos.org/PASTSYMPOSIA.HTML

International Archives of Photogrammetry and Remote Sensing. Proceedings for the main congress (held every four years) and for the mid-term symposia (held once in the four years between congresses) can be found at: www.isprs.org/publications/archives.html

7.5 Websites

At the time of writing the following websites provide useful information, details of projects and free software:

Heritage3D project: Information and guidance on the use of laser scanning in cultural heritage, www.heritage3d.org

The English Heritage Big Data project at the Archaeology Data Service: Guidelines on archiving of archaeological data and lists of software packages (including free data viewers), www.ads.ahds. ac.uk/project/bigdata/

The English Heritage Aerial Survey and Investigation team: Information on the team's aerial archaeology survey work, including their experience of airborne laser scanning, www.english-heritage.org.uk/aerialsurvey

International Society for Photogrammetry and Remote Sensing (ISPRS): See Technical Commission V Close-Range Sensing: Analysis and Applications, Working Groups 2 and 3, www.isprs.org/technical_commissions/tc_5.aspx

Laser Scanning Internet Fora: www.laserscanning.org.uk and www.3dlaserscanning.org

7.6 Training

Manufacturers of laser scanning equipment and software will be pleased to provide training. Other organisations that may be able to provide sources of training include university departments and commercial survey companies.

8 Glossary

3D Having three-dimensions, characterised by Cartesian (x,y,z) co-ordinates.

airborne laser scanning The use of a laser scanning device from an airborne platform to record the topography of the surface of the earth.

ADS Archaeology Data Service, University of York.

CAD Computer aided design or drafting.

CIPA International Committee for Architectural Photogrammetry.

cultural heritage Refers to tangible and intangible evidence of human activity including artefacts, monuments, groups of buildings and sites of heritage value, constituting the historic or built environment.

data voids Sections within the point cloud, more than twice the point density of the scan in size, which contain no data despite surface information on the object itself.

DEM Digital elevation model, a digital model of a surface that can be manipulated by computer programs. This is the broad term that encompasses both DSM and DTM.

DSM Digital surface model, a topographic model of the earth's surface (including terrain cover such as buildings and vegetation) that can be manipulated by computer programs.

DTM Digital terrain model, a topographic model of the bare earth that can be manipulated by computer programs. Also know as digital ground model (DGM).

EDM Electromagnetic distance measurement.

geometric accuracy The closeness of a measurement to its true value. It is commonly described by the root mean square (RMS) error.

geometric precision The distribution of a set of measurements about the average value, which is commonly described by the standard deviation. All reference to the standard deviation of a quantity should be accompanied by the probable error value eg ±3mm (67% probable error) – sometimes referred to as repeatability.

GIS Geographical information system.

GNSS Global navigation satellite system, the generic term for satellite-based positioning systems that provide global coverage.

GPS The Global Positioning System, a US satellite navigation system used to position an aircraft during an airborne survey, or used as a ground based survey technique.

LAS Abbreviation for laser scanning data format – LAS.

laser Light amplification by stimulated emission of radiation: an electronic-optical device that emits coherent light radiation.

laser scanning The act of using a laser device that collects 3D co-ordinates of a given region of a surface automatically and in a systematic pattern at a high rate (hundreds or thousands of points per second) achieving the results in (near) real time.

lidar Light detection and ranging, often used to refer to airborne laser scanning but can also apply to some ground based systems.

mesh A polygonal subdivision of the surface of a geometric model.

metadata Data that is used to describe other data, an essential component of the data management process.

model An expression that should be qualified by the type of model, eg geometric model. A geometric model is, typically, a digital representation of a three-dimensional shape.

peripheral data Additional scan data collected during the scanning process, but not explicitly defined in the project brief.

point cloud A collection of XYZ co-ordinates in a common co-ordinate system that portrays to the viewer an understanding of the spatial distribution of the surface of a subject. It may also include additional information, such as an intensity or RGB value. Generally a point cloud contains a relatively large number of co-ordinates in comparison with the volume the cloud occupies, rather than a few widely distributed points.

point density The average distance between XYZ co-ordinates in a point cloud.

recording The capture of information that describes the physical configuration, condition and use of monuments, groups of buildings and sites, at points in time. It is an essential part of the conservation process (*see* the Venice Charter – International Charter for the Conservation and Restoration of Monuments and Sites, May 1964).

registration The process of transforming separate point clouds onto a common co-ordinate system.

repeatability Geometric precision (*see above*).

scan orientation The approximate direction in which the scan is made if the system does not provide a 360-degree field of view.

scan origin The origin of the arbitrary co-ordinate system in which scans are performed. When the scan origin is transformed into the site co-ordinate system it becomes the scan position.

scan position The location, in a known co-ordinate system, from which a single scan is performed. If the system does not perform a full 360-degree scan, several scans may be taken from the same scan position, but with different scan orientations.

scanning artefacts Irregularities within a scan scene that are a result of the scanning process rather than features of the subject itself.

surface normal A vector at right angles to a flat surface or to a plane tangential to a curved surface. The normal is often used in computer graphics to express a surface's orientation.

survey control Points of known location that define a co-ordinate system in which all other measurements can be referenced.

system resolution The smallest discernable unit of measurement of the laser scanning system

terrestrial laser scanner Any ground-based laser device that collects 3D co-ordinates of a given region of a surface automatically and in a systematic pattern at a high rate achieving the results in (near) real time.

TIN Triangulated irregular network, a vector-based representation of a surface made up of irregularly distributed nodes and lines that are arranged in a network of adjacent triangles.

CASE STUDY 1

Combe Down Mines, Bath

type: phase-comparison laser scanning
keywords: industrial archaeology, cave surveying, stone mines, visualisation

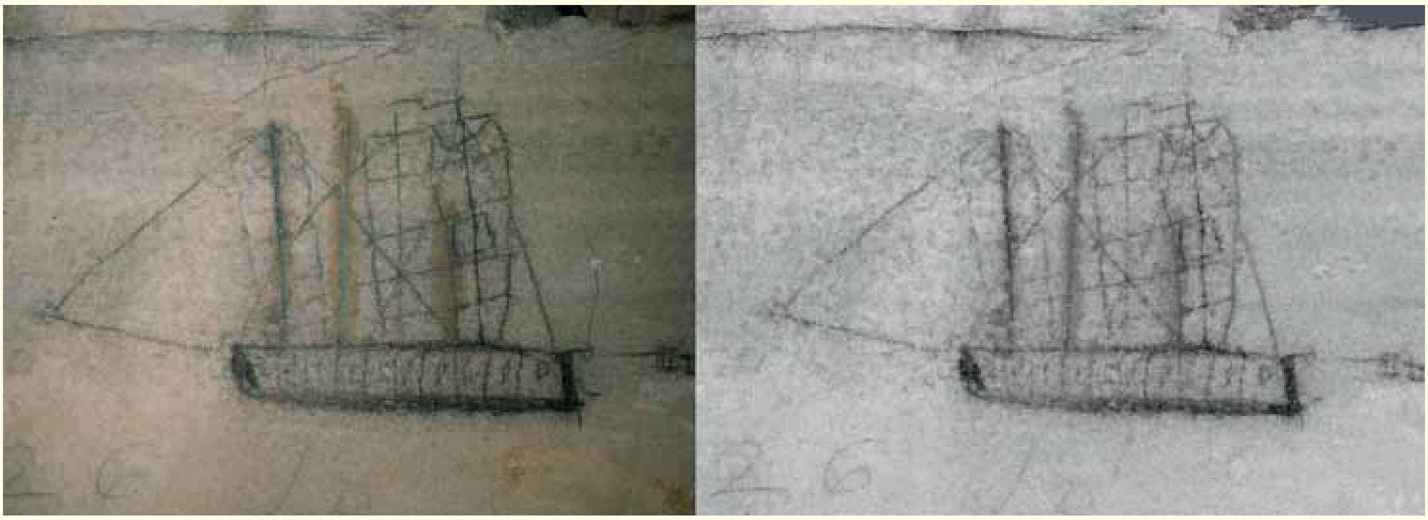
Introduction

The Oolitic Limestone mines at Combe Down were worked, mainly during the 18th and 19th centuries, to provide much of the stone used for the construction of buildings in Bath.

In 1994 an underground survey of the mines was carried out, which found that irregular mining and robbing of stone from supporting pillars had left the mines unstable and that the majority of the mines had between two and six metres of overburden. The village of Combe Down sits above the mines and was in danger from roads and buildings collapsing into the mines.

Bath and North East Somerset Council's bid for a two-phase stabilisation project was accepted in August 1999 by English Partnerships and work to stabilise the mines began. The project not only needed to stabilise the mines by infilling, primarily with foam concrete, but also needed to create a record of the historic mine system as work progressed. The mines were so unstable that no access was allowed beyond specially constructed, steel-protected roads or walkways. Working in conjunction with Oxford Archaeology, APR Services scanned the site from November 2006 to 2009, in roughly monthly phases, as roadways were driven into new areas. Once scanned, the areas were filled with concrete.

Fig CS1.1 (above) Faro LS880 protected for scanning.
Fig CS1.2 (below) Miner's graffito of a ship: photo (left) and laser scan (right).



Instruments and software

APR Services used Faro LS880 and Photon 120 laser scanners in conjunction with a Leica total station. For the various processing stages, Faro Scene, Pointools Edit, Rhino and Pointools Plug-ins, Polyworks and 3D Studio Max were used.

Why was scanning selected?

Carrying out a survey in this working environment is difficult. The necessity to gather as much of the data as possible from only the walkways made scanning the obvious solution, and made it possible to capture the general detail of the mines as well as specific artefacts in great detail. We therefore needed to use a light and fast scanner at relatively short ranges (0–30m). Thus we opted to use the Faro LS880, a phase-comparison, shorter range scanner, enabling us to 'blanket' scan the area quickly and easily, in detail, from numerous locations. Once back in the office we could register, combine and thin the data to an even spacing when processing.

For ease of scanning and to protect our equipment all scanning was done without a laptop – pre-setting the scan parameters before going underground. This way we only had to push the scanner start button to record to the internal hard drive. We further protected the scanner by wrapping it in cling film and with a thin, clear plastic sheet directly over the mirror to protect it from drips.

What problems were encountered?

There was limited light and cramped working space underground, so procedures were kept as simple as possible. The main problem for the survey was access to scan areas. To scan as much as possible, and to get unrestricted views, we often placed the scanner just beyond the walkway, up to an arm's length away either on a tripod or balanced on rocks. Controlling the scanning was also a problem, because lack of access beyond the safe corridor made it difficult to spread control around the scanner. We were provided with details of the primary control survey stations by the on-site mine surveyors. Additional control and scan targets were observed from these stations. Using the scanner's inclinometer helped to minimise the problem of scanner control because the scanner reference system is normal to the ground and only needs orientation.

What was the deliverable output?

Using Faro Scene, we carefully checked and filtered the data to remove imperfections in the point clouds, then registered and put them into the correct grid system. We then imported all data into Pointools Edit and combined them into a single point cloud. Due to the high resolution of the scans, the data were filtered when imported, to give a uniform 10mm spacing on all scan surfaces. This gives sufficient detail to identify all the main features within the mine. We presented the cloud data to the client as a 10mm, uniform-spaced point cloud for each completed phase. The pillar plan map of the mine was updated each time, adding all roadways and pillars; and we made a 'fly-through' movie so that the archaeologists could verify the progress. We referenced all scan locations on the plan so that data from specific locations can be reprocessed at any time at a higher resolution. For example, to get precise measurements and images, scans of original miners' graffiti were re-processed at 2mm spacing.

We scanned all accessible areas until the mines were finally backfilled, creating a permanent point cloud data record. All scanning phases were then re-combined and the result was divided into 50m grid squares for easy reference and use. Late in 2009 we made fly-through movies on multiple camera headings of the 3D point cloud, to provide a virtual tour of the mines. Accompanied by specially commissioned music, these movies were shown on giant screens to the people of Combe Down, so that they could experience the world that had existed below their village, but which they had never seen.

In 2010 we were commissioned to make modelled fly-through animations. We chose three routes, over 1km in total, through the main recorded sections of the mine system, making more than 20 minutes of video. To do this we used Pointools Edit to carefully separate the rock surfaces from man-made features within the point cloud. It was also necessary to separate the floor, ceiling and pillars so they could be meshed into the video using Polyworks. We accurately modelled the metal roadways, buildings, staircase, etc from the point cloud using Rhino software. Meshes and models were imported into 3D Studio Max for texturing. We created precise animation paths in Pointools and then imported into 3D Studio Max for rendering the final animations into high resolution.

Fig CS1.3 Stills from the modelled fly-through animations.

CASE STUDY 2

Alnwick Castle metric survey

type: time-of-flight laser scanning, ortho-rectification
keywords: Alnwick Castle, 3D laser scan, orthoimages, Pointools, Scan Station 2, Leica Cloudworx

Introduction

Alnwick Castle is the second largest inhabited castle in England. It has been the home of the Percys – Earls and Dukes of Northumberland – since 1309. The first Lord Percy of Alnwick restored the castle, primarily as a fortress, in the early 14th century; portions of this restoration remain today, including the Abbot's Tower, the Middle Gateway and the Constable's Tower. Since then, generations of Percys have continued to make their mark and the castle has benefited from an extensive conservation programme.

In 2010 the Alnwick Estates commissioned metric surveys of the castle keep, the Constable's Tower and the Barbican in preparation for their 2010 maintenance and restoration programme. As part of this work, English Heritage required us to submit detailed stone-by-stone elevations, outlining the proposed works. The intricate shape of the castle made conventional surveying techniques impossible. Therefore the Estates were keen to use either photogrammetry or 3D laser scanning to produce the final plans.

Instruments and software

It was decided to use 3D laser scanning provided by Digital Surveys, using a Leica Scan Station 2. The individual scanner set-ups were decided after an initial site

Fig CS2.1 Scanning the castle parapets.

inspection. Set-ups were positioned square-on to each true elevation of the castle and, where possible, at equal distances from the castle walls and from each other. We established a network of targets around the castle and co-ordinated with a Sokkia reflectorless EDM (REDM) total station to provide the survey control.

Fig CS2.2 Castle keep point cloud.

Each laser scan was done at a 3mm point density. At each scanner set-up we took 360-degree colour photographs with the internal camera, then duplicated these with an external camera. The external photos were shot in RAW with a Sigma fish-eye lens, to be burnt to the point cloud later. Care was taken to take photographs in the best lighting conditions, to avoid shadows on the data. Finally, we took additional photographs square-on to each elevation with a conventional camera lens.

We cleaned and registered the resulting point cloud using Leica Cyclone software. We then burned the colour images to the point cloud. In total, more than a billion data points were collected. We then exported the data from Cyclone as a gridded PTX file to retain the vector normals of each point. Finally, we imported the data into Pointools View Pro so that orthoimages of each elevation could be generated.

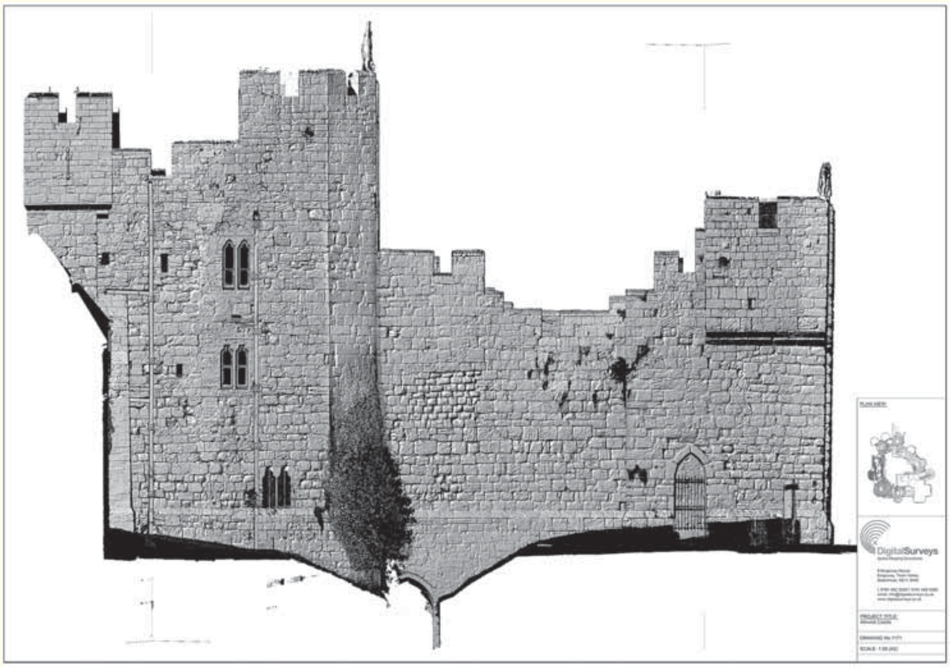


Fig CS2.3 Example final elevation deliverable output.

Why was scanning selected?

The Estates selected laser scanning because it enabled fast, non-contact data collection and documentation of the entire castle from ground level, eliminating the need for scaffolding. Laser scanning also has the potential to produce much additional output that could be used by the Estates. The initial brief was to provide 2D elevation drawings. However, after experimenting with Pointools, we decided in consultation with the client that orthoimages would provide a higher level of accuracy and detail while taking a fraction of the time to do.

What problems were encountered?

The point cloud data created high-resolution monochrome orthoimages; However, trying to create colour output resulted in several problems, as the colour coming from external images had to be matched to the point cloud. As the height of the castle increased, the photos became more distorted resulting in decreased accuracy. Building angles sometimes made it necessary to take scans at varying distances, generating different intensity values. When combined into a single image the data are blurred. To overcome such blurring we used Pointools to apply a single colour to the point cloud, followed by lighting effects to highlight the mortar detail.

What was the deliverable output?

We created orthoimages in TIF format at 300dpi resolution and attached these to AutoCAD files for printing at 1:20 scale. As such TIF format images are large, it was decided to convert them to JPG file format, redusing file sizes by 90%, but with no visual degradation of the images. Hard copies were then printed and archived by the Estates Department.

CASE STUDY 3

Surveying the Hayla Tower, Liwa Oasis, Abu Dhabi, UAE

type: phase-comparison laser scanning
keywords: historical digital archive, recording, laser scanning

Introduction

We were instructed by Donald Insall Associates, historic building consultants, to undertake a digital archival survey of the Hayla Tower in the Liwa Oasis, Abu Dhabi, United Arab Emirates (UAE), ultimately for the Abu Dhabi Authority for Culture and Heritage (ADACH). Liwa Oasis is 150km south-west of Abu Dhabi in the Rub-Al-Khali desert. It is a crescent shaped oasis comprising 50 or so villages and a small town called Muzayri. The oasis is of historic significance to the people of the UAE, as it is the birthplace of the ruling families of Abu Dhabi and Dubai. The Al Nahyan family moved their principle residence from Liwa to Abu Dhabi in 1793.

The Hayla Tower is in a small clearing of date palms at the west end of the oasis and is said to have been built in the 19th century during the wars between Liwa and Ajman. It is assumed that what remains today is the surviving structure of an original and largely un-restored watch tower. Interestingly, the surviving small entrance to the tower was probably originally set c 2m above ground level and it is believed that the tower originally stood significantly higher than it is now, meaning that the lower portion is preserved for future investigations. The circular tower is constructed from roughly coursed rubble stone bedded in mortar and the whole structure is in such a fragile state that ADACH installed a lightweight scaffold around and through the tower as a temporary measure while this investigation report was prepared. As part of this report, Greenhatch Group Ltd provided accurate survey drawings and photographs as a basis for recommendations for the consolidation and repair of the tower.

Instruments and software

We surveyed the tower internally and externally, and its local surroundings, using a phase-comparison, Leica HDS 6000 laser scanner with point resolution set at approximately 2mm within a 10m radius. We used precise tilt-and-turn field targets to provide registration. We used a Leica TCRP 1201 total station to collect reflectorless EDM (REDM) observations that tied each scan position into a minimum of four control points. We took 360-degree photographs once each scan was finalised, using a collimation calibrated Manfrotto camera bracket and a Canon EOS 5D digital SLR camera. With these data we made 360-degree panoramic images for each scan position and coloured the point cloud data. A two-man survey team did this work in spring 2010. They completed the work, excluding travelling to and from site, in a single day. The presence of a scaffolding system on site enabled us to establish eight external scans at fairly uniform positions in a 10m radius around the tower perimeter. The tower interior was scanned from one central location at heights of *c* 1.0m and 1.8m, using the same four co-ordinated field targets, to achieve comprehensive coverage around the interior. The survey point cloud data were saved directly to the hard drive of the HDS 6000 for the sake of efficiency and to avoid the cables and hardware that are needed for computer link-up. The data were downloaded to a laptop and to an

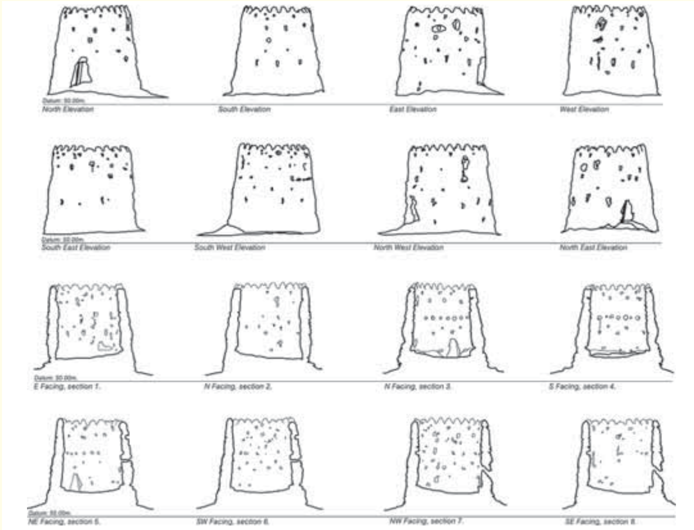


Fig CS3.1 (above) The Hayla Tower and its date palm, oasis setting.
Fig CS3.2 (below) The heavily braced interior.

Fig CS3.3 Plans and elevations of the Hayla Tower.

external hard drive and analysed before leaving site.

Back in the UK, we used Leica Cyclone software to import scan data and co-ordinated tie points to provide a complete, fully registered point cloud of the tower and its surroundings. These point cloud data were exported into AutoCAD using Leica Cloudworx to produce appropriate plan, elevation and sectional 2D DWG drawings using selective orthogonal slicing commands.

Why was scanning selected?

The Hayla Tower is generally considered to be the most significant historic building in Liwa Oasis. Because it is difficult to portray the circular and irregular nature of the tower by the more traditional method of photogrammetry, Donald Insall and Associates decided that laser scanning would be the best way to record it comprehensively. The tower was covered by scaffolding, externally and internally, and the use of laser scanning and multiple point cloud coverage mitigated the likelihood that scaffolding would obscure the scan data. Internally especially, photogrammetric results would have been severely compromised by difficult access and limited fields of view. In contrast the use of a central, 360-degree rotating laser scanner was well suited to such a challenging environment.

What problems were encountered?

It was difficult and stressful getting a laser scanner, a total station and all accompanying survey equipment to Abu Dhabi with just two survey staff. There was no guarantee that it would all arrive on time and be fully functional.

Once at the oasis we had to address the difficulties of establishing a permanent survey control system. We decided to use survey disks fixed to the bases of five palm trees, which were locally co-ordinated by REDM. We could use these to re-occupy our co-ordinate system by resection when so required. We needed to ensure that our scan locations covered all areas where scaffolding might obscure detail from other scan locations. To survey the outside of the tower we decided to use the partly regularised pattern of the scaffolding to divide the tower perimeter into eight segments. Internally, the mass of scaffolding proved exceptionally difficult to work around, so again a method was devised splitting lower and upper central coverage to ensure that all the necessary data were acquired.

These scans needed to be tied into control points, however, and it was difficult to observe four field targets by total station using the same lower internal tripod setting. Battery power was crucial, as there was no means of charging equipment on site. As we knew how many scans per battery we could achieve, we devised a strategy that worked well until the last scan, for which a low power setting had to be used to complete the work.

Temperature also affected the survey, rising from *c* 30˚C in the morning to 45˚C by midday. The higher temperature exceeded the scanner's operating parameters, so we had to periodically cool it down with the air conditioning in the hire car. The dry environment and fine sand also hindered surveying, and coated our equipment and instruments in a layer of dust. The scanner lens and the total station had to be cleaned regularly. If additional survey days had been required it is likely that the dust would have affected the rotating mechanisms of both instruments.

What was the deliverable output?

The purpose of the survey was to supply digital data for archive and interpretation of the surviving structure. The brief was to supply 2D AutoCAD DWG files and high-resolution PDF files for inclusion in a conservation strategy plan. We provided a topographical survey, a base plan and additional horizontal slices up the tower at one-metre intervals as AutoCAD 2D files. We also issued eight external orthogonal elevations of the tower and eight similarly orientated internal sectional elevations. Each external and internal elevation was backed up by partially scaled, rectified (within the constraints of a circular structure) digital photography to use in identifying specific areas of repair.

In addition to the standard 2D drawings we also made a Leica Truview DVD, which provided three-dimensional interactions with each scan position and a hyperlink into a 360-degree panoramic photograph of each survey position. Finally, a complete archival record of the site data was provided in English Heritage standard formats for other uses, such as 3D modelling or monitoring analysis.

CASE STUDY 4

Surveying of historical structures and topographical features at Fountains Abbey, Ripon, North Yorkshire

type: phase-comparison laser scanning integrated with traditional topographical survey techniques
keywords: historical digital archival, recording, laser scanning, topographic survey

Introduction

The English Heritage Estates Team commissioned us to undertake a detailed topographical survey of the river course and a stone-by-stone elevation survey of the tunnel entrances at Fountains Abbey in North Yorkshire. Set in the Skell Valley with cliff faces on both sides and the river running through it, Fountains Abbey is the largest monastic ruin in the country. It is a masterpiece of 12th-century building ingenuity.

The Abbey was founded in 1132 by exiled Benedictine monks from St Mary's Abbey in York and was admitted into the Cistercian Order three years later. The introduction of the Cistercian system of 'lay brothers' was important to Fountains Abbey's development, as it underpinned the foundation's great wealth. Monastic life at Fountains was ended abruptly in 1539 by Henry VIII's Dissolution of the Monasteries. The site was stripped of building materials for the next 70 years. In 1768, the Aislabie family of nearby Studley Royal acquired the Fountains estate, thus joining the two estates and bringing the abbey ruins within the Studley Royal landscaped garden. The extensive Studley Royal water gardens, created by the Aislabies between 1720 and 1770, are arguably the most important example of the genre in 18th-century England.

UNESCO awarded the site World Heritage Site status in 1987 and it is managed by the National Trust. The site is also in the guardianship of English Heritage, which provides maintenance support and a strategic management plan. Owing to its location, in recent years the Abbey has been affected by flooding, probably caused by changes in the environment. Consequently, improvements to water-flow through the site and the condition of the tunnel apertures are being investigated. Survey drawings from the Greenhatch Group provide a basis for investigation and subsequent consolidation.

Fig CS4.1 Surveying the tunnel entrances.

Instruments and software

The Greenhatch Group undertook the topographical survey and the stone-by-stone elevation survey using a combination of a Leica HDS 6200 laser scanner and a Leica TCRP1201 reflectorless EDM (REDM) total station. The point resolution for the stone-by-stone work was set at the minimum 1mm spacing at 10m, and 10 scans were undertaken over, around and within the tunnels to provide the comprehensive data required to create the sections and elevations, using a combination of point clouds. All scan positions were tied into a minimum of four control points: tilt and turn, precise field targets, co-ordinated by REDM from the nearby total station.

After finalising each scan, we took 360-degree photography, using a collimation calibrated bracket and a Canon EOS 5D camera to enable the production of panoramic images and colourised point data. We also took additional high-resolution images using a wide angle aspherical lens to aid AutoCAD drafting from the point clouds in the office. We undertook the topographical survey scanning in the same manner: we observed field targets by REDM before making a scan of the environment from each location at a 3–5mm resolution. We made each scan before any standard detail pole work and scan locations were orientated, to ensure complete coverage. At the same time, we concentrated on more difficult subject matter, such as detailed plinths, paved surfaces, ornate window openings and the like.

The resultant dataset was a three-dimensionally correct series of string lines and level data gained by conventional total station and fixed-prism detail pole (up to the base of structures and plinths only), together with a comprehensive point cloud that could be orthogonally sliced to provide secondary 2D detail. We used LSS software to register, traverse-adjust and co-ordinate the total-station string line and control-point data, and to export it into AutoCAD as a 3D and a 2D dataset with contours. We then used the Leica Cloudworx AutoCAD plug-in to further manipulate the 2D AutoCAD data and to selectively orthogonally slice the point cloud to provide the required high-resolution topographical and stone-by-stone drawings.

Why was scanning selected?

For the topographical survey, the vast extent of detailed masonry, tunnels and vaulted areas required integration between traditional total station observations through detail pole and contemporary laser scanning techniques. Only this way could the necessary resolution for the 2D AutoCAD drawings be achieved.

Making a comprehensive laser scan of the site simultaneously with observations to a detail pole provided the assurance that all areas could be drawn up with confidence and no important historical detail was omitted. We could have only made a detail pole topographical survey, but the level of 2D cartographical information was greatly improved by a detailed point cloud dataset.

The environment was equally suited to laser scanning or to photogrammetry to provide stone-by-stone drawings of the tunnel entrance and side walls. Cost was an important issue, however, and the requirement for 2D stone-by-stone drawings – rather than for more involved 3D data – made laser scanning more suitable. Large, open mortar joints between stones also facilitated 2D digitising using point cloud data drafting. We have had mixed results with this process, and clearly defined mortar joints are key to successful 2D stone-by-stone drawings using laser scanning technology.

What problems were encountered?

The complexity of the site made interpretation, drafting and manipulation of the correct components difficult. This was especially true, for example, when trying to present an underground tunnel below overhead detail, such as the Cellarium vaulted ceiling still intact above.

Perhaps the biggest problem, however, was the interaction with the general public on site. The survey was made in mid-summer to ensure water levels were low for the river bed survey; but this also meant that visitor numbers were at their highest, as this was during school holidays.

For public safety, warning notices and laser safety procedures were observed, but as an extra precaution, we also surveyed all the areas of higher public interest (the Cellarium for example) early

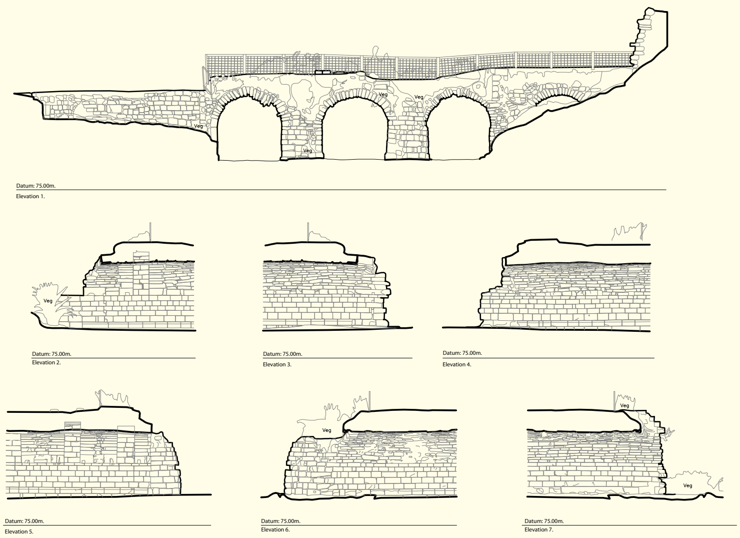


Fig CS4.2 Stone-by-stone tunnel elevations.

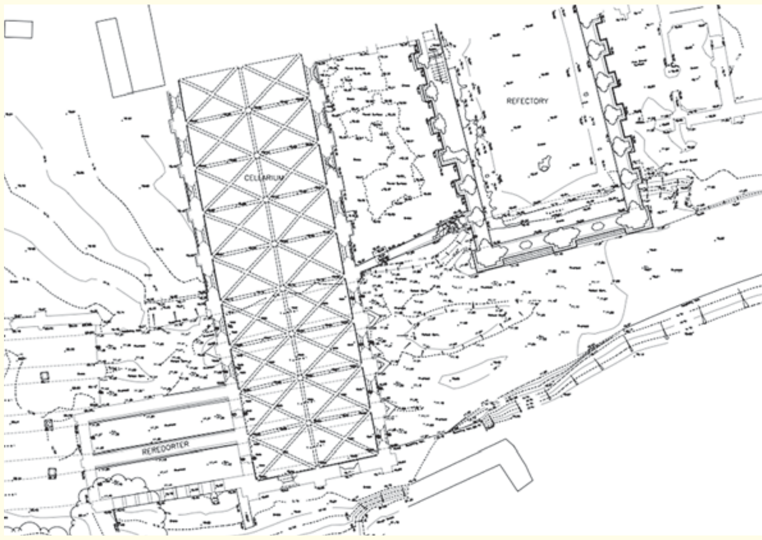


Fig CS4.3 Resultant detailed 2D topographical drawings.

each morning before the site opened to visitors. Interaction with the public was nevertheless inevitable. Detail pole topographical work could continue, but laser scanning data had to be constantly checked or stopped when sightlines were reduced during busy periods.

What was the deliverable output?

The majority of the work was related to a detailed topographical survey. However, one important requirement of the specification was to ensure that some form of 3D functionality was available. By surveying all main topographical features and levels by traditional total station and detail pole in 3D string-line, we could create a comprehensive 3D triangulated DTM surface in DWG form. This would complement the more detailed 2D topographical drawings.

We presented the 2D topographical drawings on overlapping 1:200 scale frames – but the level of detail provided was equal to 1:50 scale. The stone-by-stone drawings were issued at 1:50 scale as 2D only AutoCAD drawings. All drawing information was checked on site by the English Heritage team and amendments made. Next, we made stable ink-on-film archive copies of each drawing. In addition, all survey data were issued to English Heritage in their standard formats, along with accompanying metadata. Finally, we made a Leica Truview DVD to ensure that the point cloud data could be further used. The DVD comprised all drawings in high resolution PDF form, together with point cloud interaction and the use of 360-degree panoramic images for each scan position.

CASE STUDY 5

West Kennet Long Barrow, near Avebury, Wiltshire

type: phase-comparison laser scanning
keywords: pre-historic monument, heritage recording, preservation

Introduction

West Kennet Long Barrow is a prehistoric burial mound, situated on a prominent chalk ridge *c* 2km south of Avebury in Wiltshire. It is part of the Avebury complex of Neolithic sites and is a UNESCO World Heritage Site in the guardianship of English Heritage.

The mound is *c* 100m long and is oriented east–west. The excavated tomb extends 10.5m into the mound at its eastern end. It comprises five chambers, with two pairs of opposing chambers on each side of a narrow passage, and a single chamber at the end. Recent research shows that the tomb was constructed *c* 3650 BC using large Sarsen boulders from the nearby Marlborough Downs and smaller limestone rocks from farther afield. Evidence suggests that the tomb was initially used for only 30–50 years as a burial site. Further evidence suggests secondary use *c* 2570–2515 BC, after which the tomb was closed by filing the interior with earth and blocking the entrance with three large stones.

The chambers were discovered by John Aubrey in the 17th century, excavated in 1859 and again in 1955. Evidence of at least 46 burials was found, now displayed in the Wiltshire Heritage Museum. Today the site is considered to be one of the best preserved and most visited burial chambers in Britain.

To facilitate West Kennet's management and conservation to ensure its survival for future generations, an accurate record of the site and surrounding landscape was deemed necessary. Our specification was to laser scan the barrow's internal surfaces and the surrounding landscape.

Fig CS5.1 West Kennet Long Barrow, view of entrance stones.

Fig CS5.2 Coloured scan data of the interior of the barrow.

Instruments and software

To meet this specification we used a Faro Photon 120 laser scanner, chosen for its high point density and accuracy, as well as for its ability to scan the short ranges required within the chambers. We used proprietary targets and tripods to ensure the maximum level of error redundancy; and a high-resolution Nikon camera to capture imagery from each scan set-up. For precise vertical alignment we positioned the camera directly above the scanner head, on purpose-built mounts, then used the images to create photo-realistic, high-resolution scans in post-processing.

We used existing survey stations to link the data to a local site system. Using this site control as a baseline, we observed all scan targets with a two-second, high-precision Leica TCR1002 total station, observing at least four angles from each station. Targets were placed around the site's periphery and on the established pathway across the top of the barrow. Inside the barrow no targets could be placed on any of the chamber surfaces, so many of the internal scans were registered using cloud-to-cloud registration. We did, however, ensure that a certain number of the scans were tied into the local co-ordinate system.

Multiple scans were made within the chambers to ensure maximum coverage and to minimise shadowing (occlusion) by protruding stones within the confined spaces. We scanned these internal surfaces with a maximum point density of 2mm, then processed the data and imagery in Faro Scene and Leica Cyclone.

The scan data were registered into a single-coloured point cloud, from which we extracted plans and elevations using Leica Cloudworx in AutoCAD.

Why was scanning selected?

Laser scanning was considered the most effective method for recording the irregular and organic nature of the tomb. The space within some of the chambers limited scanning distances to less than 0.8m, which meant that many other recording methods would have been impracticable. The archaeologists in 1859 and 1955 recorded the burial chambers using conventional methods to produce 2D plans. The use of laser scanning, however, provided a complete 3D record of the tomb and surrounding landscape, from which conventional 2D plans and cross-sections could be extracted. The 3D data are accessible to the project partners using Leica Truview, which enables a virtual tour of the monument.

What problems were encountered?

Adverse winter weather proved to be an issue. Snow fell on the first day of scanning, so only the interior could be recorded. Later, when completing exterior scanning, gusting winds made maintaining equipment stability difficult. Frequent visitors, including several coach loads, caused further disruption; some seemed more interested in the survey work than in the monument itself. In some cases we had to use Photoshop to remove people from the edges of some images.

What was the deliverable output?

We provided the raw and registered coloured point clouds, and photographs; also a Truview database, with which users can view the scan data and take measurements. From the data we extracted plans of the barrow and quarry ditches, showing features and contours over the entire area; a plan of the chambers at c 900mm above floor level; and a series of sectional elevations showing stonework.

Sources

Bayliss, A, Whittle, A and Wysocki, M 2007 'Talking about my generation: the date of the West Kennet Long Barrow', in Alex Bayliss and Alasdair Whittle (eds) *Histories of the Dead: Building Chronologies for Five Southern British Long Barrows*. *Cambridge Archaeol J* **17** (supplement).

www.english-heritage.org.uk/daysout/properties/west-kennet-long-barrow/history-and-research/

www.sacred-destinations.com/england/west-kennet-long-barrow.htm

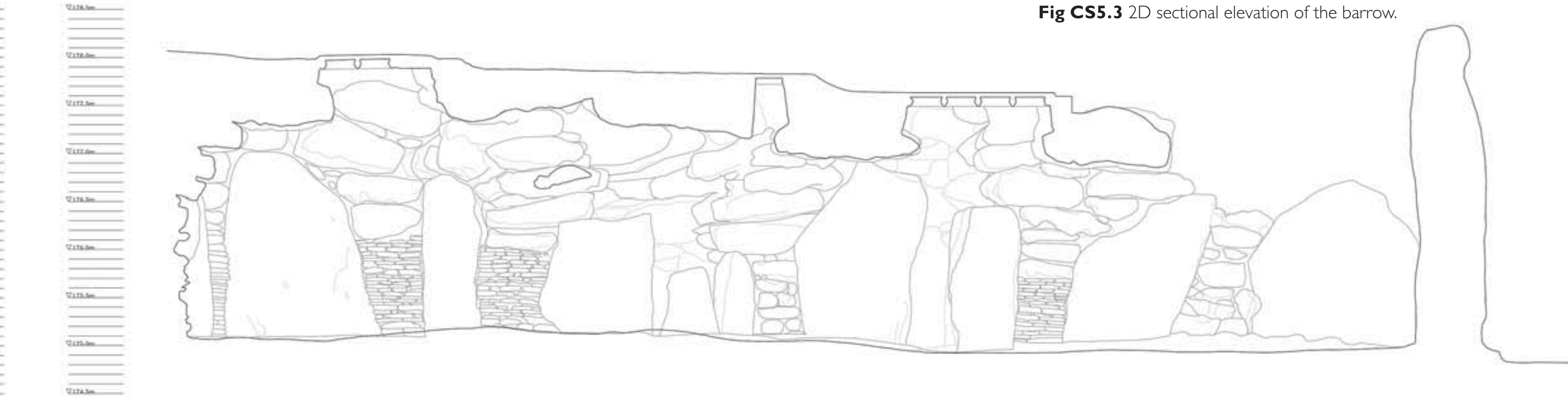


Fig CS5.3 2D sectional elevation of the barrow.

Fig CS 6.1 Gilded bronze Anglo-Saxon great square-headed brooch.

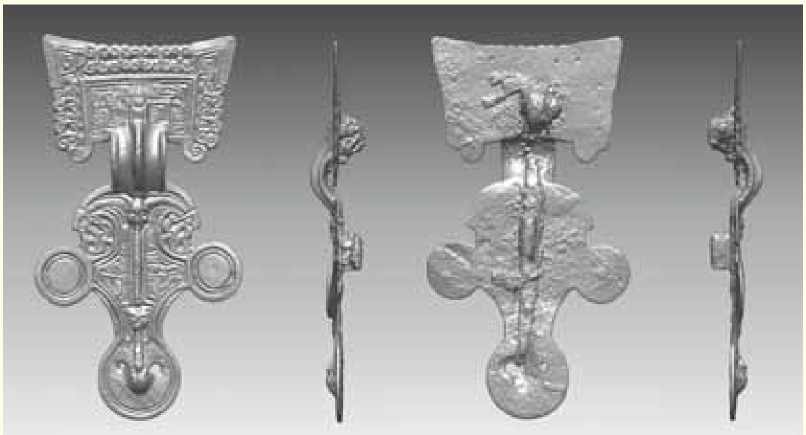


Fig CS6.2 Screenshot of the 3D computer model of the brooch.

Fig CS6.3 Finished replica brooch

CASE STUDY 6

Scanning and replication of a gilded bronze Anglo-Saxon brooch

type: arm-mounted triangulation-based laser scanning
keywords: 3D laser scanning, documentation, non-contact, replication, Anglo-Saxon, brooch

Introduction

Conservation Technologies made a replica of an Anglo-Saxon great square-headed brooch (*c* 160 mm × 90 mm; dated AD 400–500) for visitors to examine and handle at the Weston Discovery Centre, World Museum Liverpool. The surface of the gilded bronze brooch was too fragile to mould, so a non-contact approach was used. We laser scanned the object to make a master pattern from the resulting computer model, using a 3D printing process. A replica was cast from the master pattern in a copper alloy. The replica brooch was gilded and finished by hand and a new clasp fitted to its back.

Instruments and software

A 3D Scanners Ltd. Modelmaker X laser scanning system with a 70mm stripe width, mounted on a 7-axis Faro gold arm was used for data capture. The system has an accuracy of +/-0.1mm in ideal conditions. The sensor head was hand-held and the working distance was maintained at *c* 50mm throughout the process. Two scanning stations were required to capture data from the front and back of the brooch. We used Innovmetric Polyworks v.10 and Inus Technology Rapidform 2006 software packages for data alignment, merging and post-processing.

Why was scanning selected?

The gilded surface of the original artefact was too fragile for direct moulding. Laser scanning enabled us to create an accurate, high-resolution digital record with minimal handling of this important object; then to 'print' a master pattern from which a mould could be taken and the replica piece cast in bronze.

What problems were encountered?

The brooch's fine detail and shiny gilded surface made necessary more post-processing work than normal to produce a high-quality polygon mesh with no voids, suitable for 3D printing. Also, alternate light and dark areas on parts of the surface made it necessary to vary laser power during scanning, to ensure complete data capture.

What was the deliverable output?

We archived the raw scan data, the final polygon mesh model, the photographs and the metadata. A full-size gilded bronze replica brooch was produced and a new clasp fitted to the back to make the brooch wearable by museum visitors.

CASE STUDY 7

A historic buildings survey at Wakehurst Place, Ardingly, West Sussex

type: time-of-flight laser scanning
keywords: conservation management plan, historic building survey, 3D survey, National Trust, Kew

Introduction

The Wakehurst Place Estate was bequeathed to the National Trust in 1964 and is administered by the Board of Trustees of the Royal Botanic Gardens, Kew. The Wakehurst Place mansion is a Grade I listed building. As part of the preparation of a conservation management plan a full, digital measured survey of the mansion was required. Wessex Archaeology (WA) and Warner Land Surveys (WLS) carried out the survey in collaboration with Richard Griffiths Architects, the principal authors of the conservation management plan.

WA and WLS made the survey according to a brief prepared by the National Trust's Territory Archaeologist. It included the production of a new digital, measured survey of the mansion, including four floor plans, long and cross sections, and the four principal elevations.

Instruments and software

We used hand, laser distance meter and total station measurements to complete the internal survey. Data were recorded using TheoLT, an interface between the total station and AutoCAD, to enable the creation of a 3D CAD drawing as the survey progressed.

Fig CS7.1 Laser scanning Wakehurst Place using a Leica C10.

We established a survey control network using a Leica TPS1200 total station, tied to the British National Grid using a Leica GPS1200 RTK GPS. All data were registered to this co-ordinate system to bring together the various metric survey datasets, excavation data and geophysics data.

We recorded external elevations with a Leica C10 laser scanner. The survey design provided a high degree of overlap between each scan to ensure consistently high-resolution data, thus facilitating subsequent drawing work. We used Cyclone to process the laser-scan data; then AutoCAD to draw the elevations.

Fig CS7.2 (above) CAD drawing of the north elevation. **Fig CS7.3** (below) Phased CAD drawing of the south elevation.

Why was scanning selected?

The mansion is a large, complex building and the requirements of the conservation management plan called for elevation drawings at 1:50 scale. The building's complexity, with a challenging array of porches, wings, dormers and gables and a complicated roofscape, make other approaches problematic – such as rectified photography or measured survey using a total station. These features, and a desire to minimise intrusive site work at one of the National Trust's most visited properties, required a bulk capture technique.

Laser scanning offered the accuracy, speed and resolution required and allowed for easy compositing of data to achieve coverage of less accessible areas.

What problems were encountered?

As is commonly the case, the sheer size of the laser-scan dataset was initially seen as a problem. but this was countered by the use of orthographic images for much of the work. These orthoimages produced from the point cloud were suitable for use as the basis of elevation CAD drawings at the scale required, which made the workflow manageable and reduced the need to handle vast quantities of data. In some cases, certain architectural details were difficult to determine from the scan, particularly in areas where scan density was reduced (ie areas that were a significant distance from any scan position or where the angle of incidence was oblique). In these cases, we used high-resolution digital images to aid in the discrimination of features.

What was the deliverable output?

From the survey data we produced 2D CAD elevation drawings, supplied both as CAD files and as hard copy prints at 1:50 scale.

CASE STUDY 8

Metric and photographic survey at Sandsfoot Castle, Weymouth, Dorset

type: time-of-flight laser scanning
keywords: conservation management plan, historic building survey, 3D survey

Introduction

Sandsfoot Castle is a Henrican castle built in the 16th century on a cliff overlooking Portland harbour. The castle keep survives in a ruinous state and the surrounding earthworks remain accessible as part of a public park. The site is a scheduled monument and a Grade II* listed building. It sits on the edge of a cliff and part of the structure has already fallen to the beach below.

Weymouth and Portland Borough Council is preparing a Stage 2 bid for Heritage Lottery Fund (HLF) funding for repair works and to improve access to the

Fig CS8.1 Panoramic photograph of Sandsfoot Castle showing the surviving structure and extent of the surrounding earthworks.

Fig CS8.2 Registered scan data showing the castle and surrounding earthworks, now a public park.

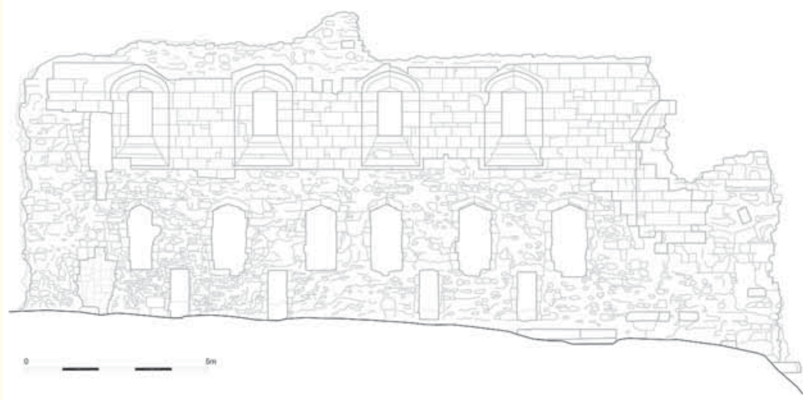


Fig CS8.3 Elevation drawing of the south-west wall.

castle. They contracted Wessex Archaeology to provide a metric and photographic survey to support the preparation of a conservation management plan that was to form part of this bid.

The survey aimed to provide accurate record drawings, illustrations and photographs of the existing monument before the repair began and also help prepare specifications for the repair and improvement works. If the Stage 2 bid were successful, the metric and photographic data were also to be used as the basis for outreach materials and for monitoring. An additional requirement was to provide a detailed topographic survey of the interior and surrounding earthworks to put into context the metric survey of the upstanding stonework.

The laser scan survey was supported by a photographic survey, including the creation of panoramic images and the capture of images suitable for rectification.

Instruments and software

We established a survey control network using a Leica TPS1200 total station, and tied it to the British National Grid using a Leica GPS1200 RTK GPS. All data were registered to this co-ordinate system.

We surveyed the site with a Leica C10 laser scanner. The survey design included a high degree of overlap between each scan to ensure a consistently high resolution of data, thus facilitating subsequent drawing work. We captured every elevation from a minimum of two well-distributed scan stations. This procedure ensured good point density and helped to eliminate shadows (occlusions).

We processed the laser-scan data using Leica Cyclone and imported the resultant registered point clouds into Pointools for the production of orthoimages and further processing. Drawing up the elevations and final CAD drafting was completed with AutoCAD.

We processed rectified photography to support the scan data using Kubit PhotoPlan. Panoramic images were produced from photographs captured with a Manfrotto panoramic tripod head. We processed the photographs with the Panorama Tools toolkit.

We did the topographic work by exporting the point cloud to ESRI ArcGIS for surface processing and analysed it using the Spatial Analyst and 3D Analyst extensions.

Why was scanning selected?

The castle ruins, though small, are challenging to record because surfaces comprise a mix of exposed rubble core, ashlar facing and brickwork. The management plan required a detailed record of the fabric and an understanding of the contours of the ground around and within the building. The instability of the ruins precluded the use of scaffolding and prolonged site work for photogrammetry was inadvisable. The exposed rubble core surfaces would make more selective recording using a total station time consuming and would not produce truly representative results.

Laser scanning offered a safe and rapid means to collect data at the required resolution and the ability to overcome problems of accessibility by integrating multiple scans. Further, as well as producing traditional elevation drawings, a point cloud better represents the remains as they stand and can be used for subsequent work.

What problems were encountered?

The small, roofless building was relatively easy to capture from a series of scan stations on three sides and within the open core of the surviving structure. The fourth elevation, however, abuts the cliff edge and some portions of the structure have already collapsed to the beach. Capture of this elevation required long-distance scans at a more oblique angle, from the beach, with resultant decreased resolution.

We overcame the challenges of site conditions with relative ease. Using a multiple scan technique and the ability to record adequate point densities at low, oblique angles enabled us to exclude obstacles such as security fences and vegetation.

It was difficult to establish a suitable visual technique for the ground surface, as the architects were unaccustomed to working with 3D data and with the edgeless nature of such archaeological deposits. Ultimately a combination of a series of selected contours, derived spot heights and a digital surface model (DSM) provided the most intelligible result.

What was the deliverable output?

We supplied a series of 2D CAD elevation drawings, presented both as CAD files and as hard copy at 1:50 scale. In addition, we provided a set of orthoimages to scale for each elevation.

We presented the topographic data as GIS maps with suitable symbology to illustrate the DSM; also, a series of GIS maps presenting the topopgraphic data as derived spot heights and contour plots. All these maps used GIS to incorporate existing data from historical sources to put the scan data into context.

We used the complimentary photographic survey data to make a series of rectified photographs of the elevations, to show the detail of the surfaces more clearly than the scan data. The panoramic photography was delivered as Quicktime VR panorama files.

We also supplied the 3D point cloud data with the free viewer version of Pointools to enable users to interact directly with the data.

CASE STUDY 9

Getting best value from a second hand cloud: Tamworth Castle, Staffordshire

type: phase-comparison laser scanning
keywords: conservation management plan, historic building survey, 3D survey

Introduction

Tamworth Castle is a Grade I listed building now housing a museum. Originating as a late 11th-century motte and bailey castle, it has undergone several phases of repair and expansion. The castle lies in the Pleasure Grounds close to the town centre of Tamworth and is a popular tourist attraction.

As a subject for metric survey the castle is extremely challenging. Its form is broadly cylindrical with curtain walls rising to 11m and the shell keep to 16m. Some sections of the cylinder are faceted, others more curved. The usual irregularities found in all historic buildings are, of course, also present, but the greatest challenge is physical access. The castle is sited on top of a steep mound, surrounded by mature trees, and its outer walls are only accessible from a narrow walkway around the base of the wall.

As part of a Heritage Lottery Fund (HLF) grant-aided project a measured survey, including laser scanning, of the castle was carried out in 2009. Initial plans, sections and elevations were produced from these data but more detail was needed to support and plan further HLF-funded work. As an alternative to extensive photogrammetry, Wessex Archaeology and Warner Land Surveys suggested a series of methods by which the existing data could be enhanced and augmented to provide the required level of detail. Central to the proposal was the idea that data could be enhanced and presented as-needed, leaving the remaining grant funding to be tightly focused on work that would be of immediate benefit to the project.

We undertook a controlled high-resolution photographic survey of the castle to provide material from which to enhance the point cloud. This was not a formal photogrammetric survey and as such did not require the use of specialist equipment beyond a high quality digital SLR.

As the survey requirement was for a series of two-dimensional CAD elevations, we divided the structure into a number of projection planes, optimally aligned to the surface described by the scan data. We then constructed the stone-by-stone elevation drawings, on these planes as 3D wireframes, using the digital photographs to provide the detail.

Instruments and software

The original buildings survey was undertaken by NGM Surveys using a Leica HDS6100 scanner. Registration was undertaken using Leica Cyclone with all scan data registered to a local grid. The data were supplied for enhancement in Leica IMP format.

The original scan data were imported into Pointools and sub-divided into manageable portions. These portions were then exported to AutoCAD 2011 with the intensity values to give pseudo-colour information and used to provide registration points for the new photographic survey. Improved visualisation of the point cloud within AutoCAD was provided by Kubit PointCloud tools which also enabled the use of single uncontrolled images as sources for the three-dimensional digitisation of features on the point cloud surface.

Orthoimages were produced for all elevations using Pointools and selected elevations were drawn using AutoCAD and Kubit PointCloud.

Why was scanning selected?

Laser scanning was chosen for data capture in order to avoid the high costs involved in providing scaffolding or other elevated platforms, which would be necessary for photogrammetric or manual survey techniques. Choosing a fast phase-comparison scanner made it possible occupy a large number of scan positions and to capture a relatively high-resolution point cloud in a short time.

What problems were encountered?

Concerns over the high noise levels often associated with phase-comparison scanners turned out to be unfounded, although the lack of colour information was problematic. This drawback was countered by using the intensity values from the scan data to provide pseudo-colour presentation of the surfaces.

Difficult access to the site resulted in a marked decrease in point density in the original scan towards the upper edges of the structure; the short stand-off from the high walls resulted in a highly oblique angle of incidence towards the tops of the walls. Protruding features also produced considerable shadows (occlusions), further exacerbated by the low-angle of incidence. We overcame lack of data for the upper reaches of the monument, and areas of shadow behind protruding features by using kite- and pole-based aerial photography. The rectification tools available in Kubit PointCloud make it possible to use such images as sources of metric information, when combined with a point cloud.

It is likely that initial extraction work also suffered from an inability to manipulate the large dataset generated by the phase-comparison scanner and that reduction of the cloud to about one-tenth of its original size then limited the detail that could be extracted. This decrease in

Fig CS9.1 Tamworth Castle; the shell keep looking from the causeway used to approach the castle.

Fig CS9.2 The complete point cloud for the castle, rendered using the intensity values.

accuracy was countered by using Pointools to handle the master dataset, as this system is capable of handling many billions of data points.

Despite reprocessing the data with more capable tools and more computing power we still faced difficulties in the smooth transition of large volumes of data between different platforms through different formats. Although these difficulties were resolved, it is a mark of the relative immaturity of these techniques that data exchange remains inconsistent; there is still no single commonly adopted industry standard interchange format for laser-scan data.

What was the deliverable output?

We produced a complete set of orthoimages for all elevations using Pointools.

We drew up a selected number of elevations stone-by-stone to facilitate subsequent management and analysis tasks. We supplied these elevations as digital CAD drawings and hard copy figures to scale. We also supplied 3D Pointcloud data and the free-viewer version of Pointools to enable users to interact directly with the data.

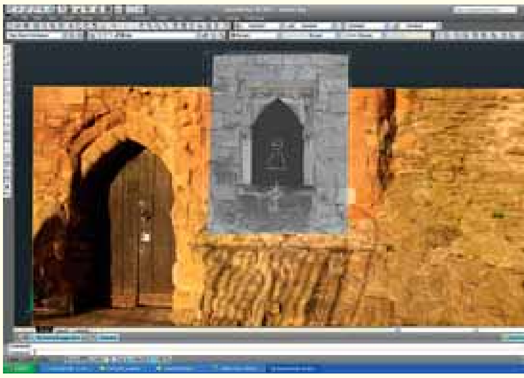


Fig CS9.3 An oriented image used for digitisation work; the photograph has been aligned to the point cloud ready to begin digitising features in 3D..

CASE STUDY 10

Laser scanning megalithic art, satellite tomb 14, Knowth, Co Meath, Ireland

type: triangulation-based laser scanning
keywords: 3D laser scanning, heritage documentation, non-contact recording, low cost, surface wrap, triangulation scanner

Introduction

The Discovery Programme has a remit to research new techniques and technologies that may have potential applications to archaeological research in Ireland. High-resolution laser scanning based on triangulation and structured-light principles had been assessed in the past, but their high cost had restricted their use. However, the availability of the NextEngine 3D Scanner HD at approximately a tenth of the price made it possible for the Discovery Programme to purchase such a scanner and assess it on a range of subjects.

Although primarily designed as a desk-based scanner, the NextEngine 3D Scanner can be mounted on a tripod, so we took the opportunity to test it on a number of sites with a range of 3D depths and resolutions. One of these test sites was Knowth in the Brú na Bóinne World Heritage Site, where we had the opportunity to use our scanner to record the megalithic art carved into both sides of a large boulder in satellite tomb 14.

The primary aim of the project was to generate a 3D model of the complete stone surface, both back and front, to prove that the NextEngine scanner could be applied to a subject as large as the stone. We also wanted to consider how the data might be exported in formats appropriate for conventional printed publication, while also looking at dissemination options of a more 3D nature.

Fig CS10.1 NextEngine scanner in operation in satellite tomb 14, Knowth.

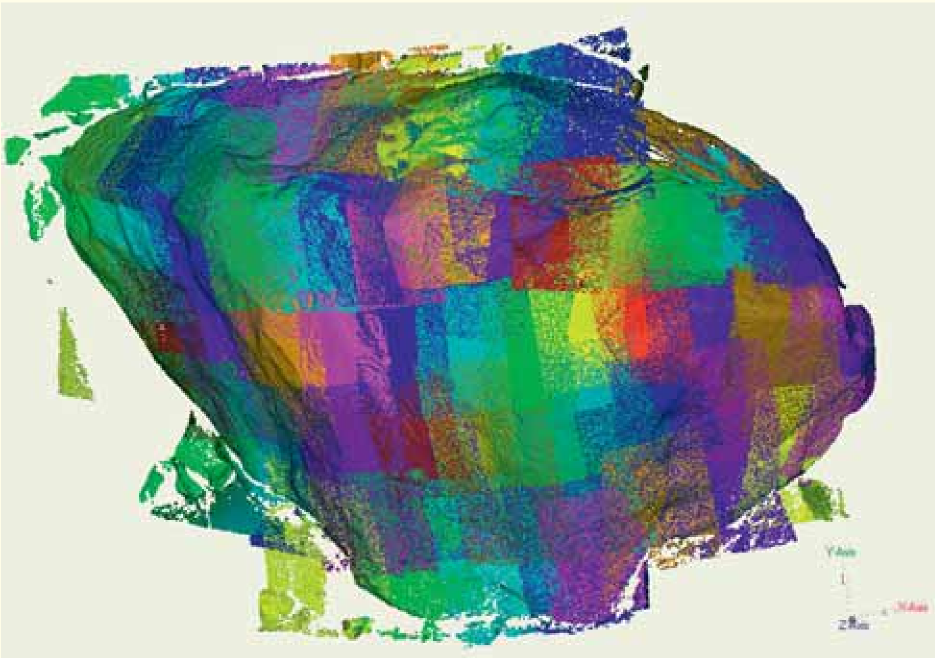
Instruments and software

We used a NextEngine 3D Scanner HD triangulation scanner (Model 2020i). The instrument was powered by a petrol generator and controlled by Scanstudio HD PRO software hosted on a Dell Precision M90 laptop. We exported data from Scanstudio HD PRO as XYZ files and did the bulk of the processing using Geomagic 10 software.

Why was scanning selected?

We used the NextEngine scanner because the design carved into the stone is extremely subtle, beyond the range that could have been recorded using a time-of-flight scanner. Given the fact that almost the entire surface of an extremely irregular shaped stone had been carved with some pattern or design, it is difficult to see what other technique could have been applied. It would have been extremely challenging to use photogrammetry, and in our experience the resulting derived-surface model would have been unlikely to match the sub-millimetre accuracy of our scanner.

Fig CS10.2 Raw data in tiles as captured by the NextEngine scanner.



What problems were encountered?

A number of problems were encountered in the recording and in the processing stages. The stone was in a small satellite tomb, which proved to be a cramped and awkward working environment. In some cases we barely had enough room to position the scanner at the required distance from the object, and had particular difficulty in linking the data from the front and back faces.

Secondly, the sheer scale of the job was an immense challenge for the scanner. The NextEngine scanner is designed for scanning small objects such as artefacts and as such the scan window can only see a relatively small area at a time – approximately 200mm × 300mm. For our scan project the intention was to tile multiple scans with sufficient overlap to attain complete coverage of the surface of the stone. This procedure presented a number of challenges. We had to treat the stone with care so we couldn't mark it or place targets on the surface. Instead, we had to keep a mental 'map' of the coverage of each scan, ensuring that both lateral and medial overlaps were maintained. For registering the scans we initially hoped to use Scanstudio HD PRO software on site as the project progressed, but as the volume of scans increased it became more and more problematic, with poorer quality fits and regular crashes. As a result, we changed our methodology and concentrated on gathering the individual scans in the field, leaving the registration process to be done off site. For this we exported data from

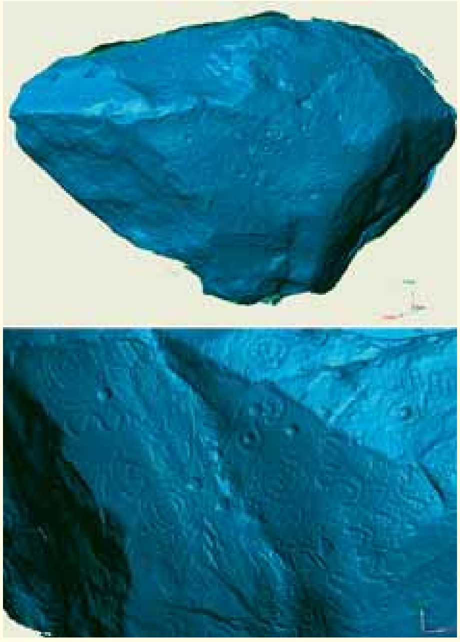


Fig CS10.3 (top) The complete surface wrap for the 'outside' face of the stone: (bottom) an enlarged portion, (centre left) of the 'outside' face. The lighting position can be adjusted to enhance different features of the artwork.

Scanstudio HD PRO separately as XYZ files and imported them into Geomagic 10.

By the end of the project we had recorded more than 100 individual scans to cover the front and back faces of the stone. We used Geomagic 10 to manually register the overlapping scans, using a minimum of three common control points visible in both scans. We then did a global registration to bind the scans tighter together to create a seamless fit. We achieved residuals of no worse than 0.2mm between scans. When all the scans had been stitched together we deleted any outlying points and created a surface wrap for each side of the stone.

What was the deliverable output?

We generated the final surface wrap in Geomatic 10 software, with which it could be examined and manipulated to great effect. Obviously this was not an appropriate output, as only users with the software could access the data. We wanted to look at the options for distributing the data in conventional printed formats and also how we could deliver the data in a 3D format that would do full justice to the quality of our model.

For the conventional plan products the problem was how to project the irregular stone surface onto the flat page to enable measurements and interpretation to be applied. For this purpose the stone surfaces were divided into a number of generalised planes and for each of these we produced an orthoimage. A key image located each of the orthoimages of the stone surface. We created more than one image for each plane, exploiting the power of Geomagic to use different lighting positions to enhance the clarity of the artwork. The accuracy of these orthoimages is clearly dependent on the variations in the surface shape of the stone, but as a tool to aid and record interpretation they have proved extremely valuable.

CASE STUDY 11

High resolution FLI-MAP lidar survey of Hill of Tara, Co Meath, Ireland

type: airborne laser scanning
keywords: FLI-MAP400, high resolution, Hill of Tara, digital elevation model, digital terrain model, micro-topography, helicopter lidar

Introduction

The Discovery Programme has had a long-standing research interest at one of Ireland's best known archaeological sites, the Hill of Tara, Co Meath. The programme has undertaken extensive topographic and geophysical survey on the ground since 1992. The terrain model generated from total station survey in the mid-1990s was ground breaking at the time and a significant factor in furthering the understanding of the archaeological remains. Our desire to increase both the extent and resolution of the terrain model was realised when the Heritage Council provided financial support to enable a high-resolution lidar scan to be commissioned.

The objective was to generate both a digital surface model (DSM) – the landscape including trees, hedges, buildings etc (also known as the first return) – and a digital terrain model (DTM) – the landscape with all upstanding features filtered out (known as the last return or bare earth). Both models would have a ground resolution appropriate to enable even the most subtle elements of the micro-topography to be seen; but this would not be restricted to simply the known monuments. Our intention was to cover the entire Tara landscape at this resolution, potentially revealing new discoveries, enhancing the understanding of the wider area and providing a definitive topographic base map, a GIS resource, to which further scientific data such as geophysical survey could be added.

Unlike most of the survey projects undertaken by the Discovery Programme the primary data were captured by a third party, as we do not own our own airborne lidar system. Instead we commissioned a lidar data provider, Fugro-BKS, and designed a survey specification that would provide us with two sets of XYZ data from which our DSM and DTM could be generated. A target resolution of 60 points per square metre was set – a nominal ground spacing of 125mm.

Instruments and software

The FLI-MAP 400 lidar system was used, mounted beneath the fuselage of a helicopter. The sensor system consists of three 150kHz lidar sensors, one pointing 15° forward, one

Fig CS11.1 Plan view of the DSM generated for the Hill of Tara from FLI-MAP data at approx. 60pts/m^2 (©The Discovery Programme).

nadir and one pointing 15° aft, two RTK GPS receivers, an inertial navigation system (INS), an 11 megapixel digital imaging sensor and a digital video feed.

Substantial data processing using FLIP7 software was completed by Fugro-BKS before the ASCII datasets were supplied to the Discovery Programme. These included: transforming the data to WGS84 and Irish Grid co-ordinates; production of the tiled ASCII DSM dataset; removal of vegetation, buildings and above surface features using a combination of intensity and video inspection; and, finally, production of the tiled ASCII DTM dataset.

Both DSM and DTM ASCII datasets had to be tiled, as the total point number in each was unmanageable – 150 million points. We created surface models using ESRI ArcGIS 9.2, utilising the 3D Analyst and Spatial Analyst extensions. First we created TIN models from each tiled ASCII XYZ dataset. These were subsequently rasterised to improve display performance and merged into a single seamless DTM and DSM. We then generated hill-shade models of the DSM and DTM surfaces to give the spectacularly detailed GIS data layers; the basis for advanced archaeological research on the site.

Why was scanning selected?

To extend the DTM for the Hill of Tara required a different approach than ground survey. Even with access to improved technologies such as robotic total stations or RTK GPS it would have been prohibitively expensive to continue modelling by ground survey. We had some experience generating DSMs through digital photogrammetric processing, but this had made us aware of some of the limitations of the technique – particularly the fact that vegetation such as trees and hedgerows are included in the model and the difficulty of achieving the high resolution required. Our experience with fixed-wing lidar – with resolutions between 0.5m and 1m – had generated spectacular models, identifying archaeological elements within the wider landscape, but failed to give the micro-topographic detail we sought for the Hill of Tara. For these reasons FLI-MAP lidar appeared to offer the ideal solution.

The results appear to vindicate our decision to use this technique. As we have not applied fixed-wing lidar to this site we have no direct comparison, but by comparing models from the neighbouring, Brú na Bóinne World Heritage Site, we believe the case for FLI-MAP is compelling, as can be seen in the following images.

What problems were encountered?

The major problems in the initial processing of the data were due to the volume of data being handled. To process the data in GIS and generate our DSM and DTM required the data to be tiled, but our deliverable output had to be complete, seamless elevation and hill-shade models. We resolved this issue by creating tiles one pixel beyond the original boundary and then averaging the overlap values when merging the tiles into the final model.

The hill-shade models were initially generated using the default ArcGIS hill-shade function angles (azimuth 315°, altitude 45°) but early examination showed the limitations in simply using one illumination angle. Features could be hidden or visually suppressed because of their aspect rather than their size. We

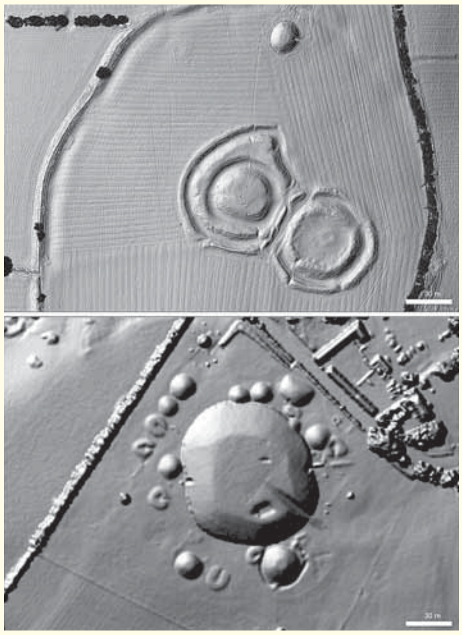


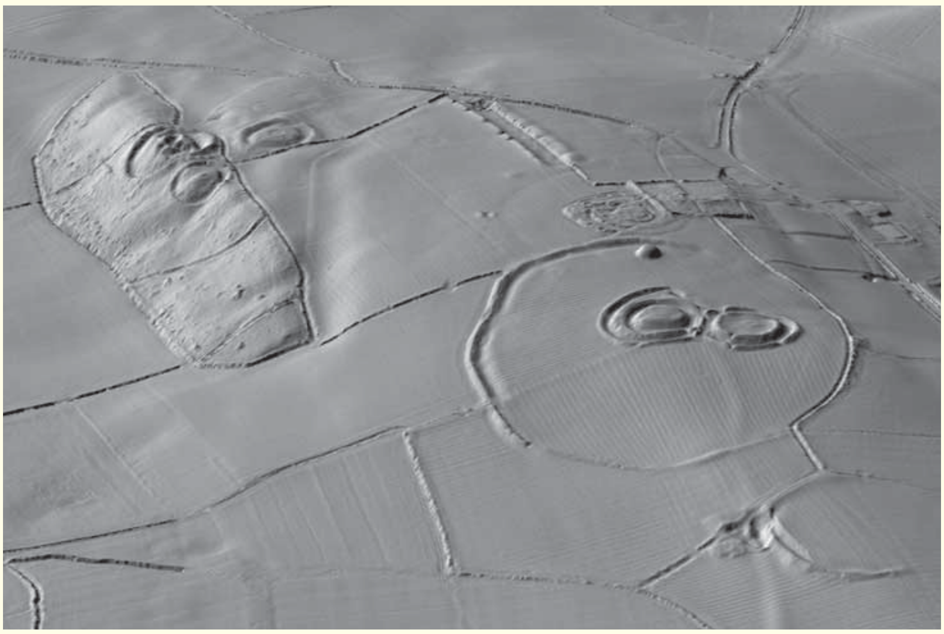
Fig CS11.2 (top) An extract from the Hill of Tara showing the level of detail reflected in a DSM generated from 125mm resolution data; (bottom) an extract from the Brú na Bóinne DSM generated from 1m resolution data. The scale of both images is the same (© The Discovery Programme).

resolved this problem by generating hill-shade models based on multiple light sources correlated to the frequency of relief features.

What was the deliverable output?

The primary deliverable outputs were the GIS products; the DTM, the DSM, and the associated hill-shade models. These were made available in the GRID format – geo-referenced image files with a 0.1m cell size. We also supplied the 100m × 100m orthoimage tiles in ECW format and the AVI files from the forward and nadir video feeds.

Fig CS11.3 Perspective view of part of the Hill of Tara DTM (© The Discovery Programme).



The GIS products (and the GIS compatible orthoimages) have been extremely well received by the archaeologists involved in research at the Hill of Tara. With the data in such commonly used formats they have been easy to distribute to colleagues and other researchers, and have been used to reveal new discoveries and enhanced interpretation of existing sites, in particular when interrogated in conjunction with geophysical survey data. From a project-planning perspective the output has proved a valuable resource in determining areas suitable for geophysical prospection.

This approach to landscape mapping has become much sought after by archaeological and heritage agencies in Ireland, and a number of projects follow this level of specification. Cost is the major determining factor, but the value in terms of research and heritage management has been recognised. From our perspective our only reservation would be the limited area we were able to cover by this technique with the funding available. It creates an artificial boundary around the Hill of Tara archaeological area at a time when research is beginning to see the hill itself as part of a much wider landscape.

Further information

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CASE STUDY 12

Chester city walls: surveying parts of a scheduled monument

type: phase-comparison laser scanning
keywords: ancient stonework survey, scheduled monument

Introduction

The city of Chester's defensive walls are the most complete surviving example in Great Britain. They are a scheduled monument and a Grade I listed building. The original defensive walls were wood and earth palisades built *c* AD 79 to defend the Roman fort, Deva Victrix. These walls were replaced with stronger stone walls between the 1st and 3rd centuries. After the Roman departure from Britain (AD 383–410) the original walls fell into disrepair. Later, *c* 907, and again in 1070, the city's fortifications were improved and extended towards the River Dee. A spur wall was added to defend the 'Roodee' ('The Island of the Cross'), a rood being a small decorative cross, which was a valuable shipping port in the 10th century.

In 2009 Russell Geomatics were commissioned by Donald Insall Associates/Gifford on behalf of Cheshire West and Chester Council to do a selective survey of the defences, to a brief overseen by English Heritage. Three main areas were chosen: Morgan's mount, King Charles (Phoenix) Tower, the Water Tower and Spur Wall.

Instruments and software

We conducted laser scanning using a FARO Photon 120 phase-comparison system. Colour was provided by a Nikon D200 digital camera mounted on a bespoke bracket. We minimised parallax issues by using a Gitzo carbon-fibre tripod with calibrated crank handle to adjust the height.

We linked the site survey to the local authority's own pre-installed 'city walls' GNSS network of control points using Leica TCRP 1201 total stations to transfer survey stations to the areas of work. The laser scan targets were observed by REDM to produce CSV co-ordinate files processed through Liscad survey software. We used FARO Scene to register the point cloud and then converted the resulting FLS files into Pointools POD format using POD CREATOR. Further cleaning, cropping and merging of files was done with Pointools EDIT. We made CAD 2D and 3D models with Pointools for Rhino and Pointools MODEL.

Fig CS12.1 FARO Photon scanner on tall tripod and the Chester city walls.

Why was scanning selected?

We used laser scanning because of its speed, comprehensive coverage, accuracy and flexibility of data manipulation. The project involved many different consultants, including archaeologists, listed building specialists, engineers and planners, so primary survey data in this form was considered the most complete and accessible for everyone. CAD processing increased this accessibility.

What problems were encountered?

We were unable to close off sections of the walls while we surveyed them. The chosen sections vary in height from 4m to 20m and can be as narrow as 1m wide at walkway level. Well meaning city visitors, joggers, dog walkers and vagrants all came along to intrude into scan cycles with various questions and opinions.

The brief required full stone-by-stone coverage and a minimum point density of 5mm. The main technical issues in the field were:

- providing control without using nails or other physical markers on the scheduled monument;
- how to place targets into the scan area without them featuring on the scan deliverables – A4 checquerboard targets stand out against medieval stonework;
- flare in individual exposures caused by changes in lighting conditions during scanning;
- members of the public appearing in the photos and obscuring the texture map of the stone wall surfaces;
- getting the scan head high enough to eliminate shadows (occlusions) around stone joints and projections;[1] and
- trees and bushes that stood close to or touched the walls and towers.[2]

Fig CS12.2 Colourised point cloud data after digital removal of vegetation in foreground.

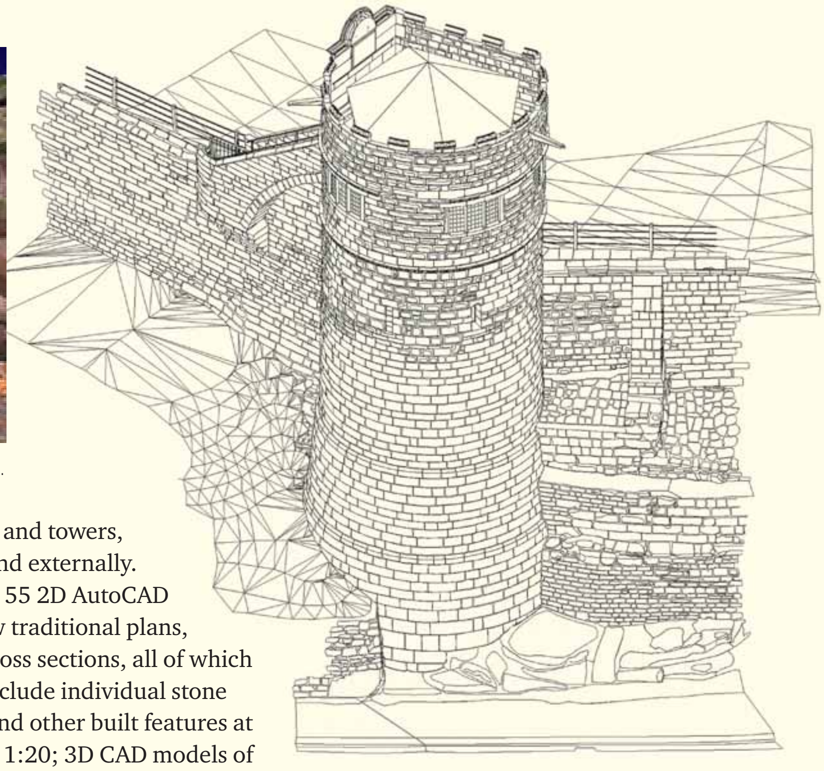


Fig CS12.3 AutoCAD 3D model with real-time hidden surfaces.

The main problem encountered while processing the data was in the areas where the point clouds overlapped. Sub-4mm resolution colour point clouds look like good quality 3D photographs when viewed singly, but when viewed in groups even the most accurate registration reduces the tightness and clarity of the colour imagery. 'Surface normals' (see Glossary) and RGB values conflicted in overlapping areas, so much further work was required to eliminate this.

What was the deliverable output?

We delivered all registered point cloud data on external 500GB USB hard drives, both as Pointools POD and ASCII XYZ files. Unprocessed original scans were supplied along with site survey control adjustment data. We also made movie files in AVI format to show animations around the walls and towers, both internally and externally.

We produced 55 2D AutoCAD drawings to show traditional plans, elevations and cross sections, all of which were drawn to include individual stone block elements and other built features at a plotted scale of 1:20; 3D CAD models of all the external surfaces were produced as surfaces/solids in Pointools for Rhino and re-imported into AutoCAD for viewing in the 3D Hidden Data visual style, on-screen in real time. We produced colour orthoimages to scale as JPG files attached to CAD drawings. We also took colour record photographs of all accessible surfaces and cross referenced these to the CAD-based line drawings.

To give maximum accessibility to all, we supplied all drawn documents as scaled Acrobat PDF files.

1 We were not able to use scaffolding or platforms. We addressed this difficulty by using a 4m high, machine-control tripod with telescopic height adjustment for photos, and a tall, carbon-fibre step ladder.

2 Some were trimmed or removed by the council before the survey, but others were yews and mature chestnuts, which could not be cut, and which increased the numbers of scans and further complicated control issues.

CASE STUDY 13

Savernake Forest, Wiltshire: lidar for mapping historic landscapes in woodland

type: airborne laser scanning
keywords: Savernake, landscapes, aerial survey, National Mapping Programme, NMP, woodland, archaeology, field survey, lidar, laser scanning, earthworks

Introduction

Since 2000 the Aerial Survey and Investigation team at English Heritage has been examining lidar data with a view to assessing their suitability for recording and interpreting archaeological sites and landscapes. In 2003 we were alerted to a fresh aspect of lidar and new potential for its use with the discovery that last-return data could be used to model the woodland floor, thereby revealing features in areas where traditional aerial survey was generally unsuitable. We tried this technique, with very positive results, on a small area of the Forest of Dean in Gloucestershire around the Iron Age hillfort at Welshbury. Gloucestershire County Council carried out further work in subsequent years over the rest of the Forest and elsewhere around the county, often in association with staff from Forest Research at the Forestry Commission.

In 2006 the Forestry Commission commissioned the Cambridge University Unit for Landscape Modelling (ULM) to carry out a lidar survey of their land at Savernake Forest, as part of planning for a management plan. The processed lidar data revealed a large number of previously unknown features within the boundary of Savernake Forest that would benefit from mapping and more detailed interpretation. The Aerial Survey and Investigation team became involved so as to carry out analysis and interpretation of these new features as part of the National Mapping Programme (NMP). This involved the interpretation, transcription and recording of all archaeological features identifiable on aerial photographs and lidar derived imagery. The project was specifically set up to evaluate the relative value of the lidar data compared with traditional aerial photography.

While English Heritage had been involved in several NMP projects using lidar data, Savernake was the first project where it was possible to map interactively from actual lidar data rather than just lidar-derived imagery.

Instruments and software

The ULM carried out the airborne lidar survey in Savernake Forest in April 2006 using their Optech ALTM 3033 system. Ground GPS support was provided by a dual frequency, Novatel receiver located at an Ordnance Survey passive recording station. We flew at c 1,000m to produce 2–4 hits per meter, and the laser footprint was set to a nominal 0.8m. Flying the survey before the deciduous canopy was fully developed and while the understory vegetation was still relatively low ensured a high degree of laser penetration to the ground surface. We converted the point cloud data to a 0.5m grid by assigning cells with the point value of the laser observation that falls within the cell. Where more than one laser observation was found in a cell we used the last one encountered in the point cloud. Empty cells were filled by smoothing from their neighbours.

The experience with Welshbury had shown the potential of just using last-return data, but subsequent projects had revealed that in many cases the remaining 'spikes' caused too much interference and a processed terrain model was the only practical solution. Staff at ULM devised their own vegetation-removal algorithm to create such a digital terrain model (DTM) of the topography of the site under the forest canopy (Devereux *et al* 2005). For the Savernake Forest project ULM, through Forest Research, provided gridded data for first return, last return and a DTM.

We converted the data into raster surfaces and read them into AutoDesk Map 2008, where it was possible to map directly from the surface. By doing this the data could be manipulated to control both the light source and the vertical exaggeration, thus highlighting features and improving their ease of interpretation.

Why was scanning selected?

The project aimed to test the potential of lidar to penetrate the woodland canopy and to enable the recording of archaeological features that survived as earthworks but were largely invisible to standard aerial photographic techniques and difficult to survey on the ground. It was also felt important to be able to test the benefits of interpretation and mapping directly from the lidar-generated surfaces in a CAD environment, something that had not been possible before advances in the software.

The secondary aspect of the survey, the capacity to compare the relative benefits of the lidar data with traditional aerial photographs, was seen as an important test that would provide useful information for those planning future surveys in wooded environments.

What problems were encountered?

Savernake Forest was the first survey area where the Aerial Survey and Investigation team had direct access to the lidar data with the capability of manipulating the data in real time. This led to quite a steep learning curve in how best to use the data. However, being able to map from the interactive surface proved much more efficient than previous surveys, which had only been able to use various lidar-derived images lit from different angles, etc.

There was an interesting effect resulting from the scale of display of the lidar surface within AutoDesk Map, whereby areas with data voids caused by dense canopy or understory could become more or less pronounced as the zoom increased. This effect lead to a degree of trial and error to establish the optimum viewing scales.

As with the earlier survey in the Forest of Dean there were some areas with a large degree of data loss. This was particularly noticeable in areas of conifer plantation, where even the last-pulse data were unable to penetrate the canopy owing to the density of foliage. This was also true where the understory consisted of bushes such as holly or rhododendron, which again severely restricted penetration. This type of data is useful for more detailed analysis, as it provides information to aid location for follow-up fieldwork and on the condition of the archaeological features.

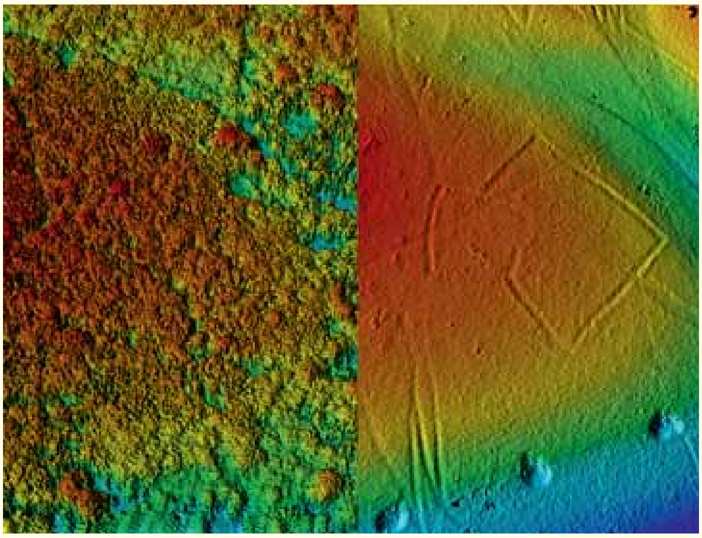
What was the deliverable output?

The ULM survey provided gridded ASCII files for first-return, last-return and a filtered DTM. Subsequent analysis of these by staff from the Aerial Survey and Investigation team and comparison with traditional aerial photographs produced a set of CAD drawings depicting all the features of interest together with attached data recording the key elements for each feature, such as its presumed date and interpretation. We recorded more details for each feature in AMIE, English Heritage's database of archaeological monuments. These data are available on the PastScape website www.pastscape.org.uk. We also assessed and synthesised the results of the survey in a report published as part of the English Heritage Research Department Report Series (Crutchley *et al* 2009).

The comparison of the relative benefits of the different sources confirmed the theory that while there are definite advantages to the use of lidar data within a wooded environment, the analysis of traditional photography should be carried out simultaneously in order to get as full a picture of the historic landscape as possible. In particular it showed that under the correct circumstances historic photographs can reveal features that have left no trace detectable by the lidar survey, but which are nonetheless important to a full understanding of the archaeology of the area.

Fig CS13.1 Savernake Forest looking south-east (© English Heritage NMR 21339/19 10-AUG-2001).

Fig CS13.2 Late Iron Age/Romano-British enclosure visible (right) on lidar-derived imagery that has been processed to remove the tree canopy (left) Lidar (© Forestry Commission; source Cambridge University ULM (May 2006)).



The practical experience of working with lidar data also fed into the English Heritage guidance note written to advise those planning to use lidar data for archaeological research (Crutchley and Crow 2010).

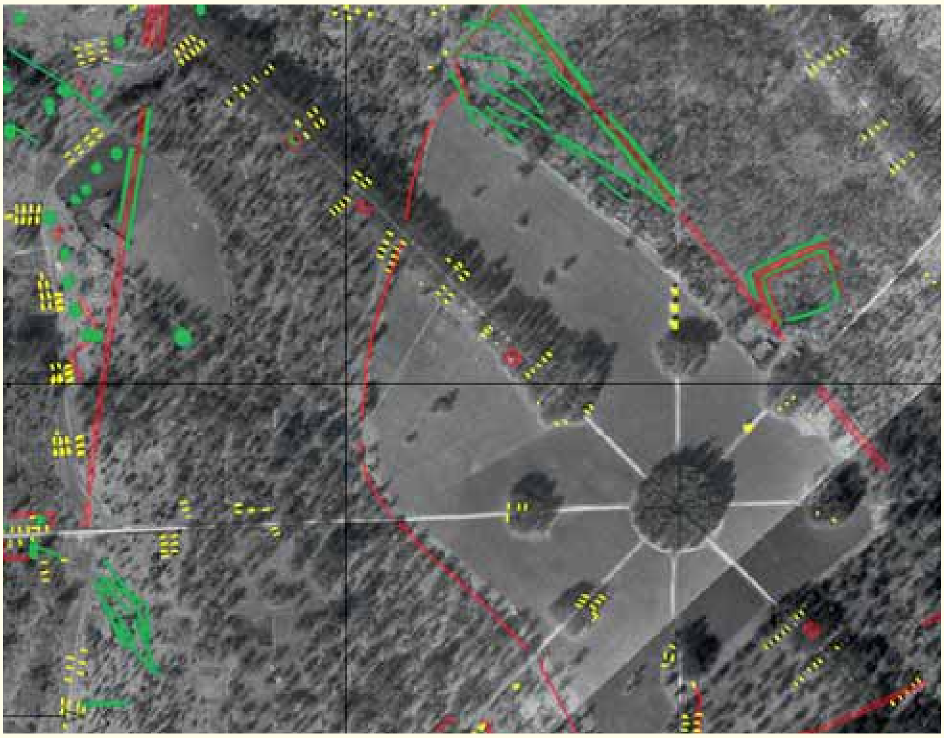


Fig CS13.3 NMP mapping overlaid on USAAF aerial photographs. Features in red and green represent those recorded as banks and ditches from the lidar data; those in yellow are structures associated with WWII activity visible only on contemporary photographs (US7PHGP/LOC/209 5010 & 5019 English Heritage (NMR) USAAF photography).

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CASE STUDY 14

Canterbury City Walls

type: phase-comparison laser scanning and orthophotography
keywords: 3DReshaper, surface model, image mapping, orthophotography

Introduction

In 2010 Canterbury Cathedral and Canterbury Archaeology asked The Downland Partnership to produce high-resolution orthophotography of a portion of Canterbury's city wall. While the flat portion of wall did not pose a problem, the two round towers were an awkward subject to survey by photogrammetry, the traditional method for surveys of this type. We decided to use laser scanning and our recently acquired 3D modelling software, Leica 3DReshaper (3DR), which utilises point-clouds to produce surfaces that can be image-mapped with high-resolution photography.

Instruments and software

We scanned the towers using our Lecia HDS 6000 in high-definition mode from eight scan positions around the base of the towers. We took photographs with a Canon 5D Mk2 22mp camera, with 24mm and 100mm Canon lenses. We registered the scans with four targets per tower using Leica Cyclone point-cloud matching. We then output the registered data into PTS format and imported them into 3DR for processing. We generated TIN surfaces to a triangle size of *c* 15mm before editing and image mapping. We saved the resulting model as OBJ files and imported it into MicroStation V8i. The final orthophotos were generated using Microstation 'save-image'.

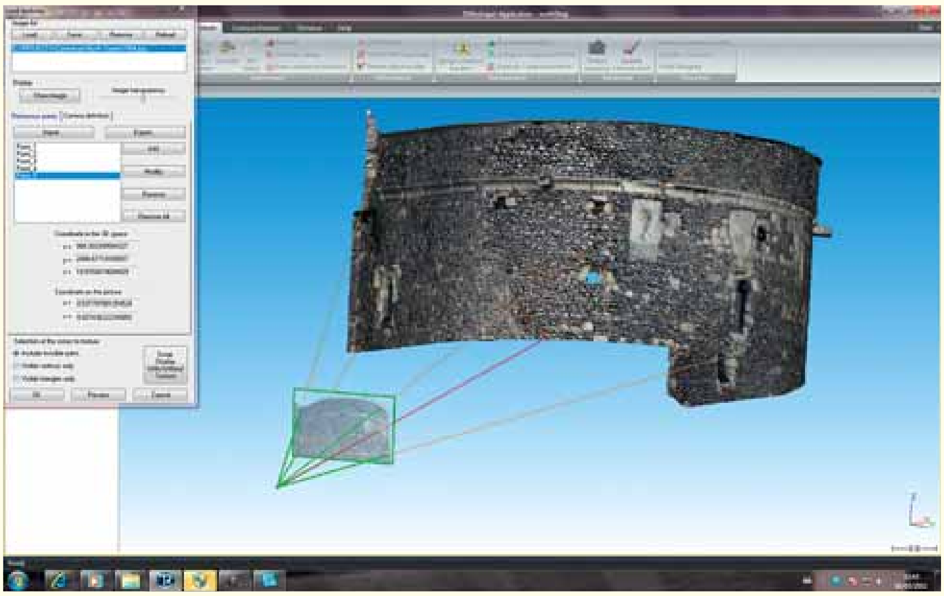
Problems encountered

The site work went smoothly. We were on site early and avoided obstruction by vehicles in the car-parks. Sometimes pigeons were difficult to frighten away.

The data processing was likewise straightforward, using familiar methods up to the point where the PTS files were generated.

The next step was new and challenging, and involved plenty of trial and error to produce the result we were looking for. The first problem was the amount of noise in the data. 3DR has some quite effective tools to enable the removal of scanner noise automatically, but it does not cope well with vegetation or pigeons. Manual editing

Fig CS14.1 3DReshaper image mapping.



of the points takes a long time, but is not as tedious as editing surface triangles. We therefore increased our point-cloud editing as time went on, the effect of which was to decrease our surface editing. Where vegetation occurs, 3DR tends to generate multiple layers of triangles oriented in all directions. Where these areas are prominent, the need to edit the surface mesh is inevitable. We found that the most efficient method of dealing with these areas was to delete all but the lowest level of triangles and then re-mesh using the hole-fill function.

Once this lengthy process was completed, the image mapping could begin. 3DR has a good intuitive system for achieving the image mapping and in general works well. There are some shortcomings, however, and these soon became apparent once we started the process. The first was that it was necessary to break the surface mesh into areas roughly equivalent to each photograph, so that only one photograph was displayed on any one area of mesh. 3DR allows the mapping of multiple images per surface and uses a system whereby it chooses to display a part of the image most perpendicular to any given triangle. This is fine in principle but relies on perfect image registration, and perfect image colour and tone matching across the whole mesh. If used, however, this method tends to create a mottled effect where one triangle displays an image from one photograph and the next triangle an image from another, and, thus of course, produces an imperfect match.

A perfect match is not practically possible as the smallest error in image matching creates local distortions and changes in focal length, which means a poor fit in the third dimension. Added to this are the problems of matching images for colour balance and tone, which is tricky when using photographs taken using natural light.

Our task became easier once we learned to break up the mesh and match only edges for fit and colour balance.

The next problem was related to the precision of the image mapping. As it was not practical to target each photograph, points of detail such as sharp stones were used. This worked up to a point but required a lot of empirical adjustment, particularly when 10–12 photographs all had to match each other. A big help would be the facility to fix the focal length and lens distortion in the software, as these parameters are laboriously worked out by 3DR photo-by-photo. At present, each photograph is orientated for position, focal length and lens distortion (if more than five points are used). The system would work better if it were possible to set constant values for focal length, particularly when these values are known through a proper photogrammetric calibration.

What was the deliverable output?

Once the image mapped surface model was completed, the requested output, an orthophotograph, had to be generated at sufficient resolution to satisfy the requirements of the client's specification. 3DR does have an orthophoto-save capability, but it saves to the current screen resolution, which is far lower than that required by the client. MicroStation, however, enables the user to set the resolution when saving an image view. As a result it was necessary to import the OBJ files into a Microstation DGN file and then create the orthophotographs as JPGs. We also provided complied VRML files along with the freely available viewer VRMLView. 3DR only allows for the export of individual mesh areas in VRML, this being necessary to keep the correct image mapping references. Therefore we compiled the individual VRML files back into a complete model using White Dune, which enabled the creation of a single VRML of each tower.

Fig CS14.2 The finished 3D model.

Fig CS14.3 The final orthophotograph.

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Cover figure: Laser scanning systems and their output datasets, applied to the full range of heritage subjects.

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