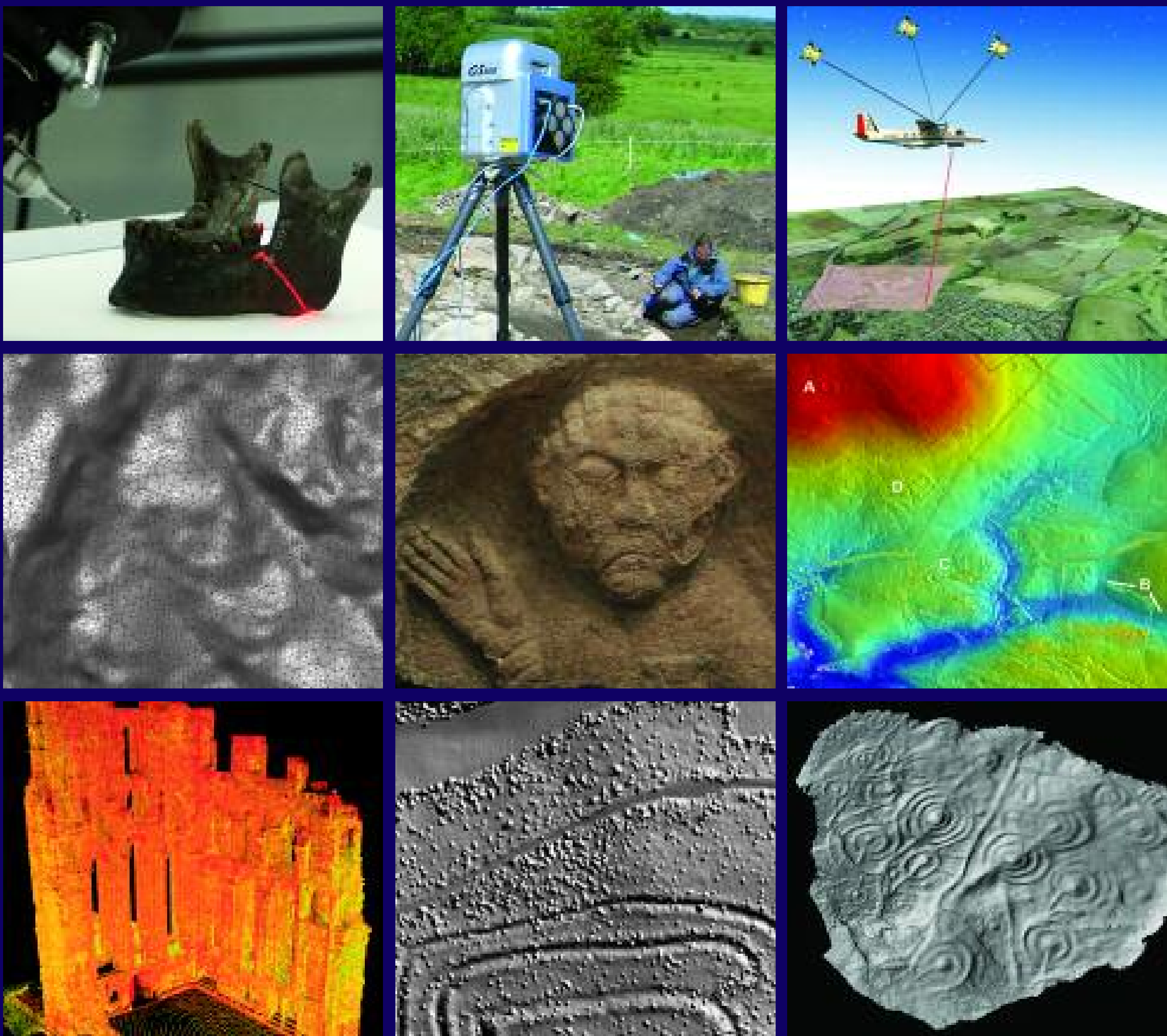
2007

3D Laser Scanning for Heritage

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



ENGLISH HERITAGE

Project overview

The Heritage3D project directly addresses four sections of the 1998 English Heritage Exploring our Past Implementation plan. The two principal aims of the project are to:

Develop and support best practice in laser scanning for archaeology and architecture

Disseminate this best practice to users along with the education of likely beneficiaries

In order to achieve these aims the project works towards five objectives:

Objective 1 – production of a guidance note that demonstrates the products that can be generated from laser scanning

Objective 2 – to update the current Addendum to the Metric Survey Specification to take into account the continuing advances in the technology

Objective 3 – to increase the knowledge base of English Heritage by forming partnerships with external survey practitioners/equipment manufacturers within the UK

Objective 4 – to promote synthesis between disciplines within English Heritage by publishing and maintaining a project website

Objective 5 – to provide workshops on the use of laser scanning to educate archaeologists, architects and engineers from within English Heritage

Contents

1 Introduction

1.1 Aims

The advice and guidance presented here aims to provide the reader with the information they require to use laser scanning appropriately and successfully within 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 on when, why and how you might want to use laser scanning, it will point to other techniques that might also be considered. Moreover, it will cover generic issues, such as data management, where the advice and guidance given will be relevant to any geometric survey techniques. As a result of this note users should be able to understand how laser scanning works, why they might need to use it and how it might be applied.

For abbreviations see Glossary.

1.2 The Heritage3D project

This note has been generated as part of the Heritage3D project. Heritage3D was sponsored by English Heritage's Historic Environment Enabling Programme (project 3789 MAIN) and undertaken by the School of Civil Engineering and Geosciences at Newcastle University. This two year project developed and supported best practice in laser scanning for archaeology and architecture, and disseminated this best practice to users. Further details on the project can be found at the Heritage3D website http://www.heritage3d.org. A summary of the case studies referred to throughout this note is given at the end of this document.

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 onto hardcopy for direct use on site. However, with the introduction of new methods for three-dimensional measurement and increasing computer literacy among users, there is a growing demand for three-dimensional digital information.

There is a wide variety of techniques for three-dimensional measurement. These techniques can be characterised 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 on the number of measurements they might be used to acquire (which is related to the complexity of the object). Figure 1 summarises these techniques in terms of scale and object complexity. While hand measurements can provide dimensions and position over a few metres, it is impractical to extend this to larger objects; and collecting many measurements (for example 1000 or more) would be a laborious and, therefore, unattractive process. Photogrammetry and 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 GPS might be used to survey similarly sized areas, the number of points it might be used to collect is limited when compared to airborne, or even spaceborne, techniques. This advice and guidance is focused closely on laser scanning (from the ground or air), although the reader should always bear in mind that another technique may be able to provide the information required.

Laser scanning, from the air or from the ground, is one of those technical developments that enables a large quantity of three-dimensional measurements to be collected in a short space of time. This document presents advice and guidance on the use of laser scanning, so that archaeologists, conservators and other cultural heritage professionals can make the best possible use of this technique.

The term laser scanner applies to a range of instruments that operate on differing principles, in different environments and with different levels of accuracy. A generic definition of a laser scanner, taken from Böhler and Marbs 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 (hundreds or thousands of points per second) achieving the results (ie three-dimensional co-ordinates) 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)

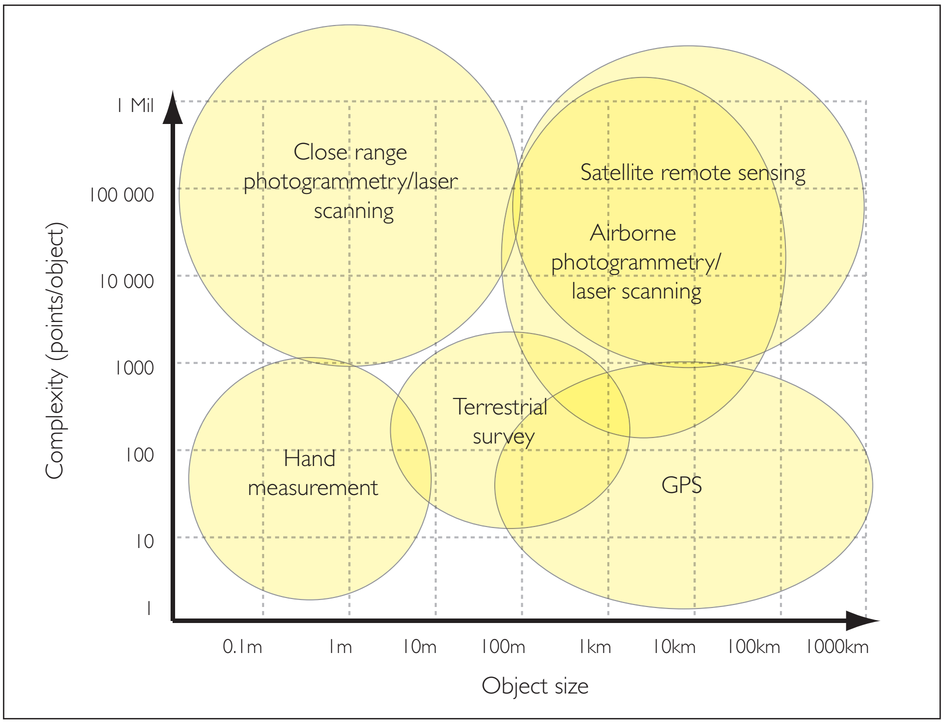


Fig 1 Three-dimensional survey techniques characterised by scale and object size (derived from Böhler presentation CIPA symposium 2001, Potsdam).

Fig 2 (left) Triangulation laser scanning (courtesy of Conservation Technologies, National Museums Liverpool).

Fig 3 (above) Time of flight laser scanning (courtesy of Newcastle University).

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

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, 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.

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. It may also include additional information, such as pulse amplitude or RGB 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.

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 sorts of questions that you'll be asking 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 be able to help inform on a particular subject by contributing to the understanding. Scanning may also improve the accessibility of the object. 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 of all types might have a use at any stage of a project. Tasks that you might find being considered could include:

- contributing to a record prior to renovation of a subject or site which would help in the design process, in addition to contributing to the archive record (*see* Case Study 11)
- contributing to a detailed record where a feature, structure or site might be lost/changed forever, such as in an archaeological excavation or 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 from which a replica model made be generated for display or as a replacement in a restoration scheme (*see* Case Study 4)

- contributing to three-dimensional models, animations and illustrations for presentation in visitor centres, museums and through the media (enhancing accessibility/engagement and helping to improve understanding)
- aiding the interpretation of archaeo-logical features and their relationship across a landscape, thus contributing to the 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 15)
- spatial analysis, not possible without three-dimensional data, such as line of sight or exaggeration of elevation

However, it is important to recognise that laser scanning is unlikely to be used in isolation to perform these tasks. It is highly recommended that photography should 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. The capture of additional data helps to protect a user as it helps to ensure the required questions can be answered as well as possible, even if the a subject has changed or even been destroyed since its survey Figs 5–12.

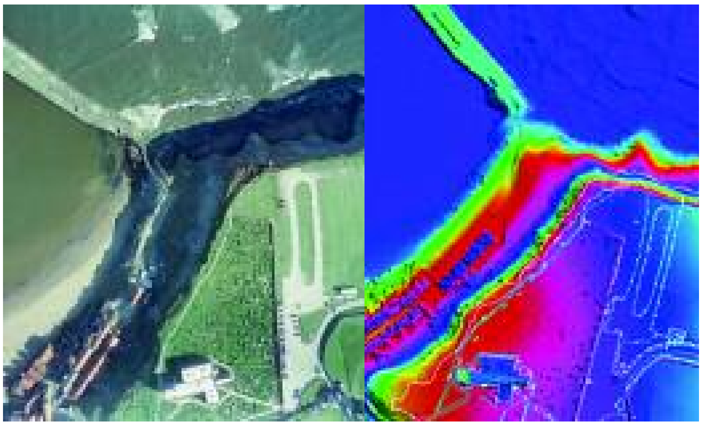


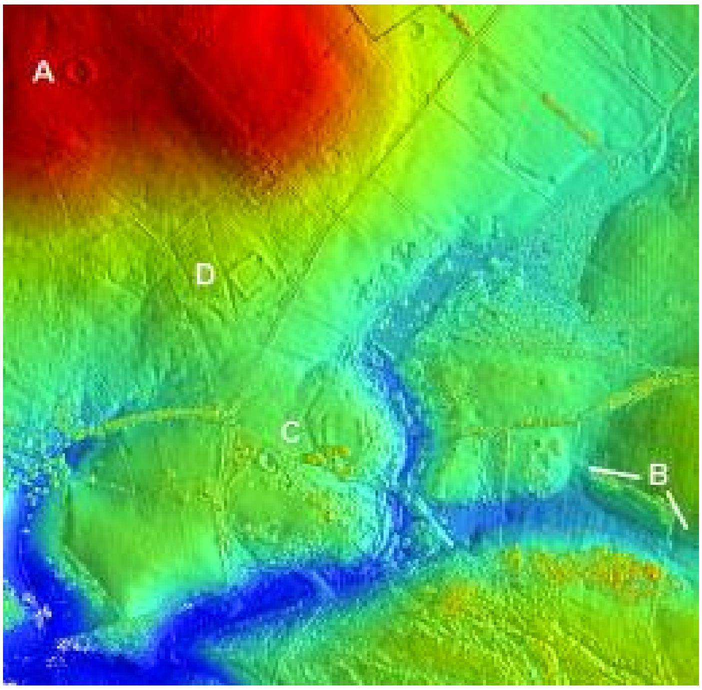
Fig 5 (left) An original and replica bust of the Emperor Caligula generated from data collected by a triangulation laser scanner (*courtesy of Conservation Technologies, National Museums Liverpool*).

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 Profile of point cloud data used for a structural survey (*courtesy Tony Rogers, APR Services*).

Fig 9 Using laser scanning to contribute to a record during excavation (*courtesy of the Discovery Programme Ltd*).



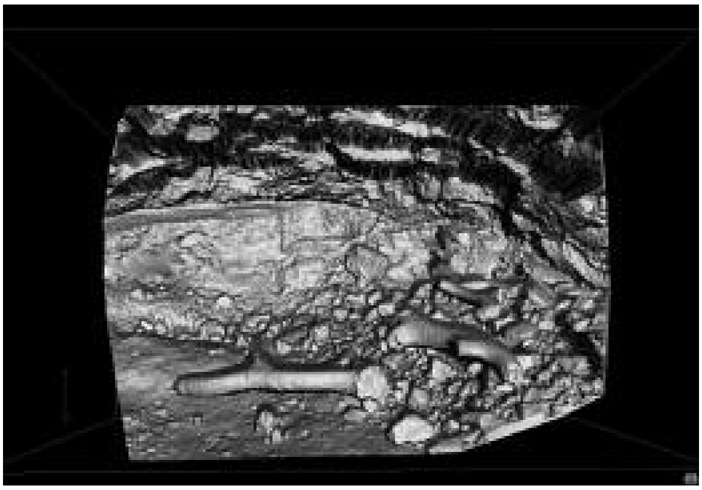


Fig 11 Laser scanning contributing to the site record of a Neolithic flint mine in Norfolk (*courtesy of Paul Bryan, English Heritage*).

Fig 12 Looking at earthworks covered by vegetation (*courtesy Simon Crutchley, English Heritage and the Forestry Commission, data provided by Cambridge University Unit for Landscape Modelling*).

Fig 10 (left) Using airborne laser scanning to understand a historic landscape: a LiDAR 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 (ULM) Cambridge University*).

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 'deliverable' required. Scanning may also take a long time to achieve the level of results you require.

Laser scanning is not as versatile as a camera, for it requires time to scan the object, whereas a camera can record a scene in a matter of seconds. Laser scanning 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 certain material types, such as marble or gilded surfaces.

While the point cloud generated by laser scanning may be useful on its own, it is more than likely that the 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 edges and discrete points, although it is increasingly used to generate two-dimensional sections, profiles and plans where supporting information, such as imagery, is also available.

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 achieved realistically. Laser scanners generally operate on one of three principles: triangulation, time of flight or phase comparison. Table 1 provides a short summary of these techniques, including typical system accuracy and the typical operating ranges. The following discussion describes each technique in further detail.

Triangulation

Triangulation scanners calculate 3D co-ordinate measurements by triangulating the position of a spot or stripe of laser

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

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) Can be used to produce data suitable for a replica of the object to be made.	50 microns / 0.1m–1m
	arm mounted	scanning of small objects and small surfaces Can be performed on site it required. May be used to produce a replica.	50 microns / 0.1m–1m
	mirror/prism	scanning small objects surface areas *in situ* Can be used to produce a replica.	sub-mm / 0.1m–25m
terrestrial time of flight laser scanners		Suitable for survey of building façades and interiors resulting in line drawings (with supporting data) and surface models.	3–6 mm at ranges up to 100m / 2m–100m
terrestrial phase comparison laser scanners		Suitable for survey of building façades and interiors resulting in line drawings (with supporting data) and surface models.	5mm at ranges up to 2m / 2m–50m
Airborne laser scanning		prospecting landforms (including in forested areas)	0.15m (depending on the parameters of the survey) / 10m–3500m

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

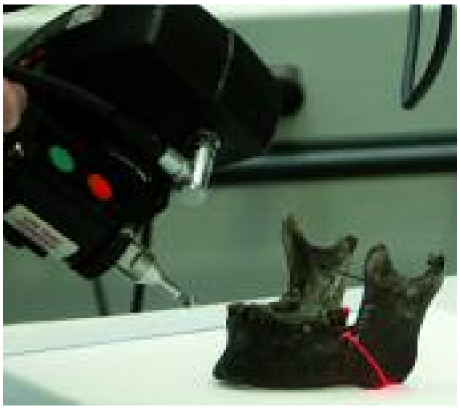


Fig 14 A laser stripe from a triangulation scanner.

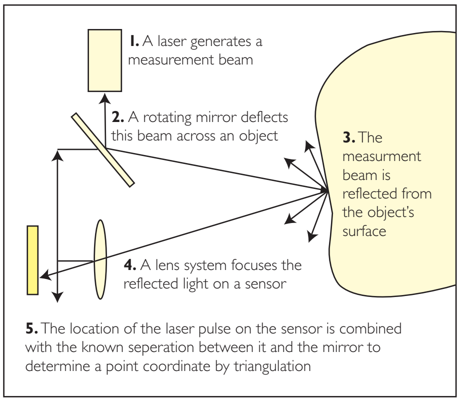


Fig 15 A schematic of a mirror based triangulation measurement system.

light. A basic outline of a triangulation system is given in Figure 15. Some triangulation systems require an object to be placed on a moveable turntable that rotates the object in front of a static scanner. Alternatively, triangulation studios or laboratories. Typically, with this type of system, the scanner-to-object distance is less than 0.5m systems may be mounted on a mechanical arm (Figure 2), which, while site portable, are more often found in specialist and commonly has a measurement accuracy of 0.1m. Although not providing the very high level of accuracy associated with arm-based scanners, there are 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 (Figs 13–15).

Time of flight

Systems based on the measurement of the time of flight of a laser pulse and appropriate to architectural conservation activities offer an accuracy of between 3mm and 6mm. Such systems use the two-way travel time of a pulse of laser energy to calculate a range.

Fig 16 A time-of-flight laser scanner, showing measurement beam and direction of scan (*courtesy of Riegl UK*).

Fig 17 A phase-comparison scanner (*courtesy of Z+F UK*).

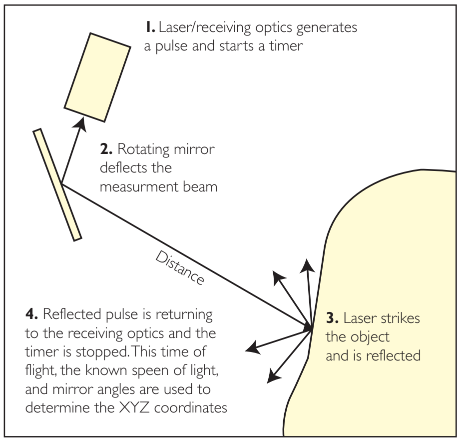


Fig 18 Measurement using a time-of-flight or a phase-comparison measurement system.

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 2m to 100m). This type of scanner can be expected to collect many thousands of points every minute by deflecting this laser pulse across an object's surface, using a rotating mirror or prism Figs 16–18.

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 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. As this is a continuous process, phase-comparison systems have much higher rates of data capture (millions of points per minute), which can lead to significant pressures on computer hardware in subsequent processing. Time-of-flight and phase-comparison systems are typically able to scan a full 360 degrees in the horizontal and often up to 180 degrees in the vertical.

Airborne laser scanning

Airborne laser scanners use laser scanning equipment based on time-of-flight or phase-comparison principles. However, it is also necessary to couple the laser scanner with sensors to measure the position, orientation and attitude of the aircraft during data collection, by GPS and inertial sensors. 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 Fig 19.

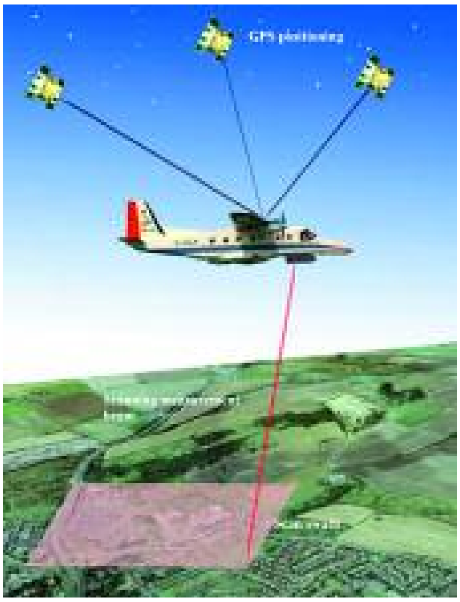


Fig 19 Airborne laser scanning.

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 the delivered digital product. Operation of the scanner is likely to be handled by a contractor. In this discussion we will restrict ourselves 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 using the final results.

The choice of software will be based on a number of factors, including data quantity, the type of 'deliverable' 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 here to highlight 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 allow 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 may not be designed to handling the large datasets generated by laser scanning, although in some cases specialist tools can be obtained to improve the performance of these mainstream tools, allowing the use of a familiar software environment.

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/she will need to ensure that the methodology is appropriate for their needs. The user will, however, need to ensure that the final product, generated from the point cloud, can be used for the task intended. He/she may want to manipulate this with a standard desktop 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 purchased. For more information on particular products, see below, section 7 Where to find out more.

2.3 Computer hardware

A standard desktop PC designed for standard office use may be insufficient to take full advantage of the generated product, or for the analysis you wish to carry out. However, desktop PCs with computing power and specifications suitable for the day-to-day use of large geometric models (assuming appropriate software is available) are more accessible and less expensive now. At the time of writing, if you are planning to buy a new machine or upgrade an existing one in preparation for the use of three-dimensional data, consider the following:

- 3D graphics acceleration: Having a dedicated 3D graphics card is one of the most important features. Choose one with at least 256 MB of dedicated video RAM. 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 memory: Plan to have at least 1 GB of RAM, although the more the better. Memory is normally installed in pairs of modules, so if you are buying a new machine, consider what will be the most cost-effective way to add more memory in the future.
- Hard disk: At least 100 GB will be required for day-to-day storage. Consider using an external USB hard disk to provide a local backup. At the time of writing, external USB disks with a 300 GB capacity cost as little as £100.
- Display: Do not underestimate the value of choosing a good quality monitor. If you have desk space, consider using a CRT version rather than the more popular flat-screen LCDs, as CRT screens often give a much better image, and are less expensive than their equivalent TFT versions.
- Processor speed and type: While having a fast processor may improve general performance, it is less important than are graphics card and RAM memory. Users should aim for a processor speed of at least 2 GHz.

While it may seem expensive to buy a whole new system, an existing desktop PC might be upgradeable by the simple addition of some extra RAM, a new graphics card and an additional hard drive (changes that might cost less than £300 at the time of writing).

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 below, section 7 Where to find out more.

3 Commissioning survey

3.1 Knowing what you want

It is unlikely that an individual requiring laser scanning will have the means or expertise to undertake the work him- or herself. It is more likely that survey work will need to be commissioned and undertaken by a specialist contractor. The following tips will help you when preparing to commission a survey:

- Consider the level of detail required and the extent of the object/area. These are often the overriding parameters used to determine appropriate survey technique and/or deliverable product.
- Start by working out what you need in order to answer the questions you have set. Try to come up with a requirement for accuracy and product. Realise that you might not need to specify the actual technique, just the product you require.
- Consider how you will use the product before it is procured/commissioned; 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. Also discuss the work with other members of the team, especially with those whose expertise is greater than yours, as other uses of the survey may be more 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 (*see* **http://ads.ahds.ac.uk/** for contact details). Ask who owns the collected data and the delivered product.
- Finally, prepare a project brief, using a standard document as a base, such as the English Heritage Metric Survey Specification.

You may wish to carry out a small project first, before committing to a larger survey, to help you fully understand the benefits and limitations of the technique. Figure 20 describes a typical project flowline. 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 needs and requirements of the survey. It should be written with direct reference to the survey specification, and should prompt the client for the relevant information. Once the project brief has been prepared it is put out to tender for survey contractors to provide a method statement giving details of how they intend to undertake the survey. The survey will then be commissioned and undertaken.

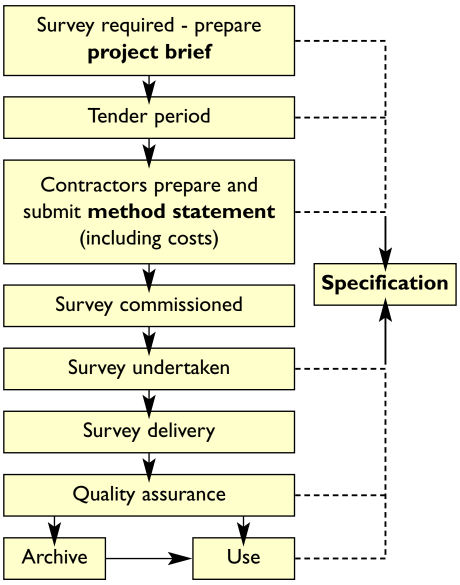


Fig 20 The survey flow line.

During this work the contractor should be guided by the method statement, but may also want 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/or on for use. Typically this is done though 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 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' you require in the project. Generally, using a point density of less than the quoted measurement accuracy will not provide useful information. For example, sampling every 1mm, when the measurement accuracy is 5mm. 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 what is the smallest sized feature he/she will require to be detected. This may not be the same over the entire object/area of survey, so it may be appropriate to employ different point densities in different areas. The scanner used should have a measurement accuracy of at least the point density of the scanning device used. (For example, a laser scanning with a given accuracy 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), trade organisations such as the Survey Association (TSA) or staff within English Heritage will be able to help you to find an appropriate contractor. Alternatively, contact other projects, individuals or other organisations and ask for recommendations.

3.4 Laser safety

Laser light, in some cases, can be harmful. To enable users to determine the potential risk, all lasers and devices that use lasers are labelled with a classification, depending on the wavelength and power of the energy the laser produces. Lasers used in survey applications may have risks associated with eye damage. The European Standard "Safety of Laser Products – Part 1: Equipment classification, requirements and users guide" (IEC 60825-1: 2001) provides information on laser classes and precautions. It outlines seven classes of lasers:

- Class 1 lasers are safe under reasonably foreseeable conditions of operation, including the use of optical instruments for intrabeam viewing.
- Class 1M lasers are safe under reasonably foreseeable conditions of operation, but may be hazardous if optics are employed within the beam.
- Class 2 lasers normally evoke a blink reflex that protects the eye, this reaction is expected to provide adequate protection under reasonably foreseeable conditions, including the use of optical instruments for intrabeam viewing.
- Class 2M lasers normally evoke a blink reflex that protects the eye, this reaction is expected to provide adequate protection under reasonably foreseeable conditions. However, viewing of the output may be more hazardous if the user employs optics within the beam.

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*
10000mm	large earth work	3500mm	500mm
1000mm	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

- Class 3R lasers are potentially hazardous where direct intrabeam viewing is involved, although the risk is lower than that for Class 3B lasers.
- Class 3B lasers are normally hazardous when direct intrabeam exposure occurs, although viewing diffuse reflections is normally safe. This class of laser is generally not suited for survey applications.
- Class 4 lasers will cause eye or skin damage if viewed directly. Lasers of this class are also capable of producing hazardous reflections. 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. Refer to the IEC standard for more information on laser safety: IEC 60825-1 2001, *Safety of Laser Products – Part 1: Equipment Classification, Requirements and User's Guide*.

Particular precautions and procedures are outlined in the IEC standard for Class 1M, Class 2M and Class 3R laser products used in surveying, alignment and levelling. Those precautions, with relevance to laser scanning are:

- Only qualified and trained persons should be assigned to install, adjust and operate the laser equipment.
- Areas where these lasers are used should be posted with an appropriate laser warning sign.
- Precautions should be taken to ensure that persons do not look into the beam (prolonged intrabeam viewing can be hazardous). Direct viewing of the beam through optical instruments (theodolites, etc) may also be hazardous.
- Precautions should be taken to ensure that the laser beam is not unintentionally directed at mirrorlike (specular) surfaces.
- When not in use the laser should be stored in a location where unauthorized personnel cannot gain access.

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 this data may have artefacts in the data owing to processing, which may be significant when performing analysis (*see* Case Study 14). Also note that the point density and measurement accuracy of this data may also not be sufficient for the analysis required. Also consider the archive issues for using such data Fig 21.

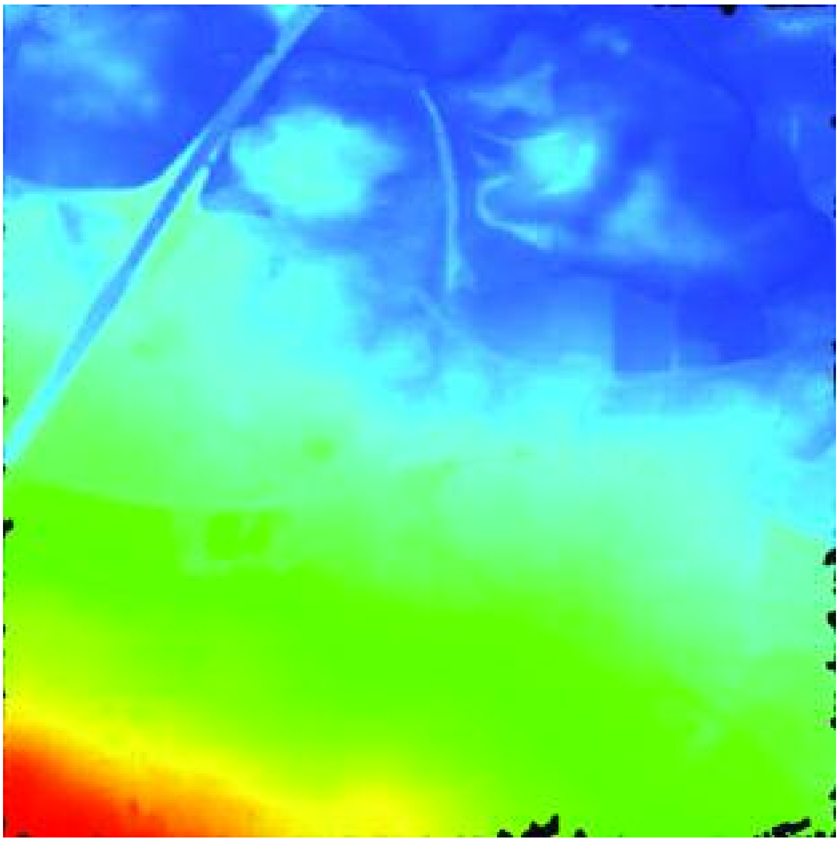


Fig 21 Elevation-shaded airborne laser scanning data (blue: low elevation; red: high elevation) for an urban area (data courtesy of the Environment Agency; image courtesy of Newcastle University).

4 From point cloud to useful information

4.1 Typical workflows

The commissioning of the survey is only the start of the survey process (*see* Figure 22 for a general example with examples of deliverable data). In order to turn scan data into a useful product the scans must first be registered, generally with the use of external survey measurements, to provide some control. This will be done by the contractor, who will then, most likely, generate some defined deliverable output. At this stage the user who has commissioned/ procured the survey will want to undertake some form of analysis to help answer the questions that were originally posed.

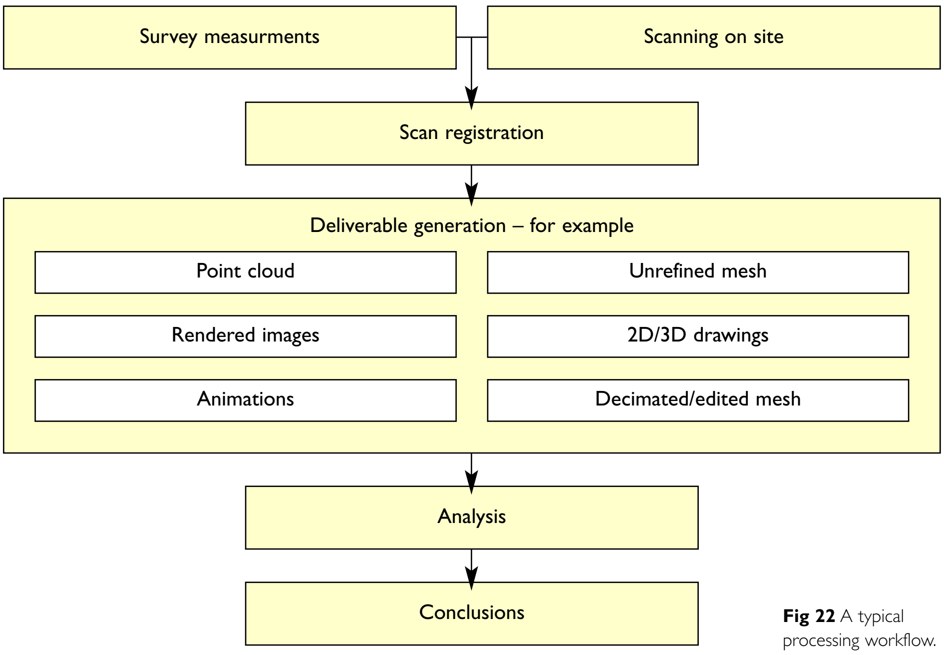


Fig 22 A typical processing workflow.

4.2 Cloud alignment/registration

For anything other than the simplest object, a number of separate scans from different locations are usually required to ensure full coverage of the object, structure or site. When collected, scans are based on an arbitrary co-ordinate system, so 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 the local site grid).

This process is known as cloud alignment, or registration. For example, scan one and scan two in Figure 23 and Figure 24 are initially in separate reference systems and cannot be used together until they have undergone a registration process, as shown in Figure 25. If the collected data needs to be referenced to a real world co-ordinate system, then it will be necessary to provide external survey measurements.

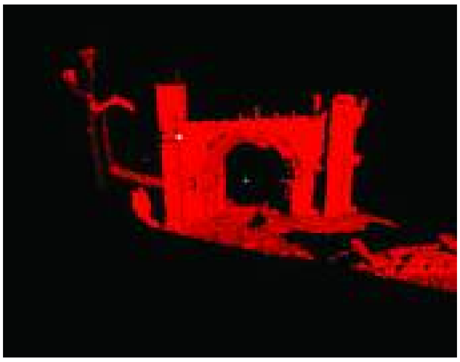


Fig 23 Scan one of the doorway.

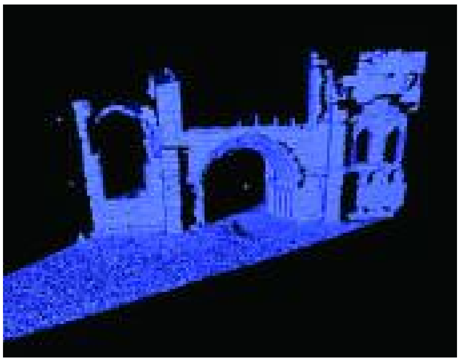


Fig 24 Scan two of the doorway.

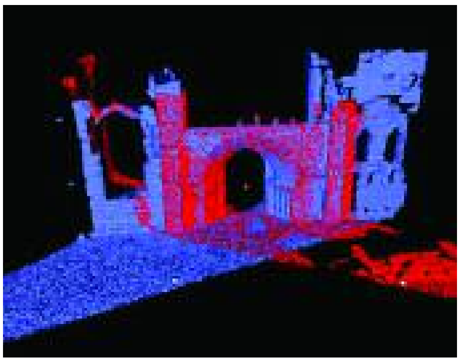


Fig 25 The scans of the doorway registered onto the same co-ordinate system.

In the case of airborne laser scanning this is accomplished directly through the use of position and orientation observations. When using an arm-mounted triangulation laser scanner, co-ordinate measurements are collected in a known system, and 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 descriptively, surface or geometric modelling. There are a number of approaches that could be used to turn the point cloud into useful information.

For a small artefact or 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 model, such as a triangular irregular network (TIN). Figures 26 and 27 show a point cloud before and after meshing, to form a TIN. In order to generate a complete model of the subject it is likely that some editing of the TIN will be required to fill holes where no data was collected. The resulting TIN is suitable for use in several types of analysis. Figure 28 shows the result of meshing point data collected by laser scanning.

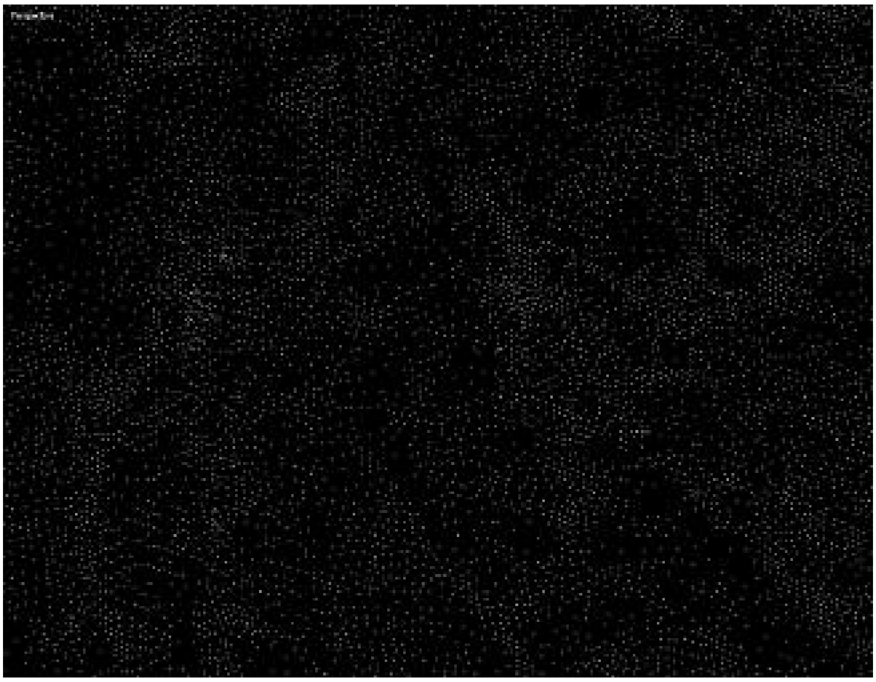


Fig 26 An unorganised point cloud prior to meshing showing a portion of the Upton Bishop fragment (courtesy of Conservation Technologies, National Museums Liverpool).

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

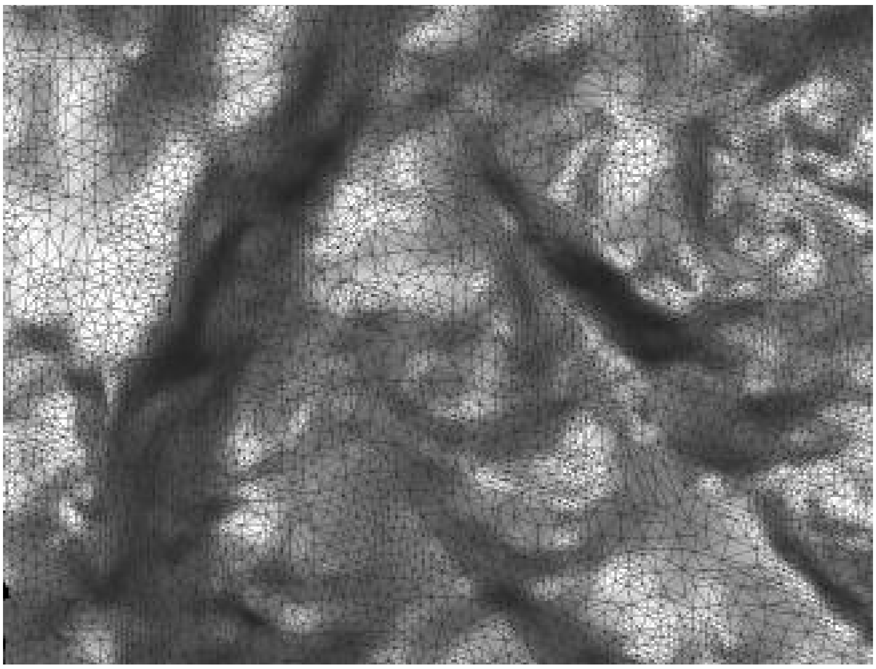


Fig 28 An original stone fragment and a reconstructed geometric model from laser scanning data (courtesy of Conservation Technologies, National Museums Liverpool).

The options for processing a ground-based system are typically more varied. While a meshed model might be required, plans, profiles and sections (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 (Figure 29). However, this is not an 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 is to undertake a classification on the available points. 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.

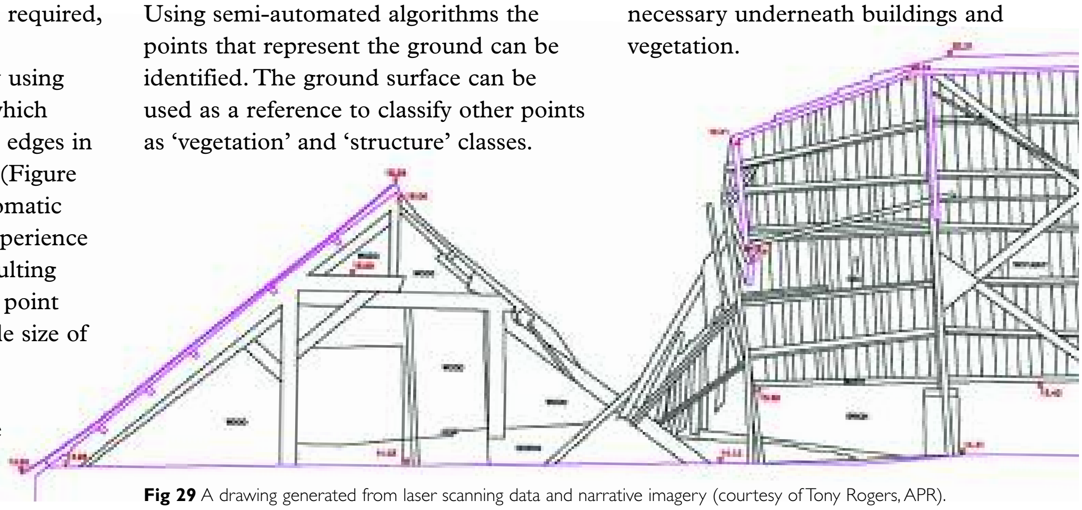


Fig 29 A drawing generated from laser scanning data and narrative imagery (courtesy of Tony Rogers, APR).

The DTM will initially be in the form of a TIN, where the surface is formed by a series of interconnecting triangles. This TIN may 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 (Figure 21 is an example).

4.4 Analysis

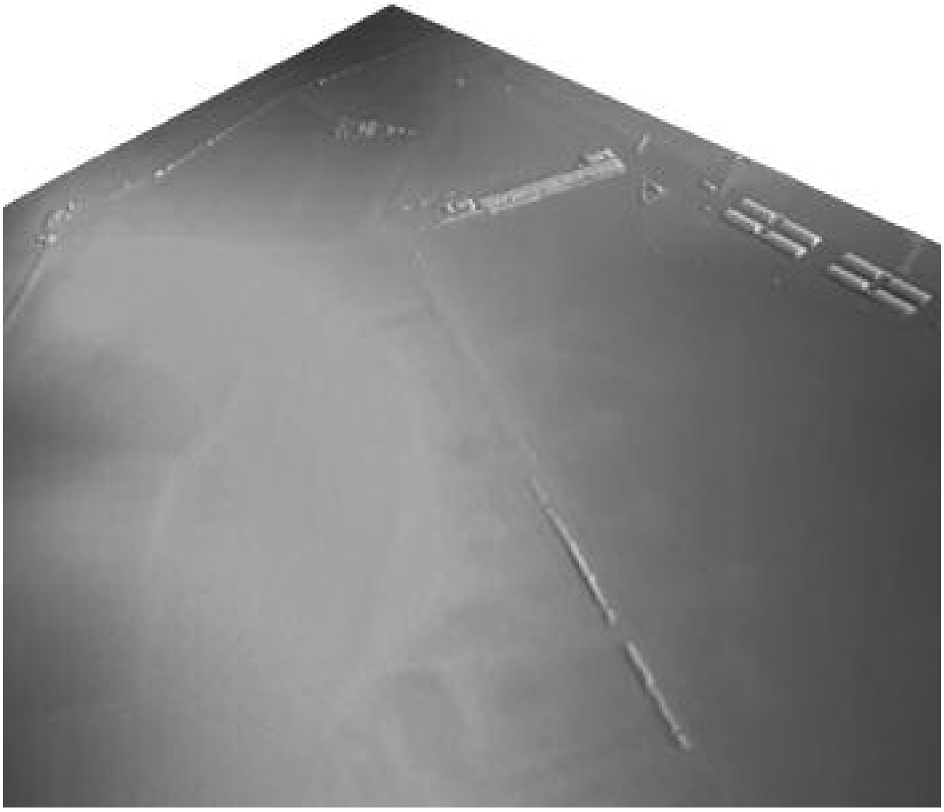
The delivery of a product derived from laser scanning data is only the start of the process of answering the original research questions. Some form of analysis is likely to be required using the final product. In fact, some of this analysis may be best done during the processing stage itself. Consider talking/working with the contractor during the initial processing. Analysis, during or after the deliverable generation of 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 14).

As laser scanning provides three-dimensional data it lends itself very 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, eg 50% of the castle is visible from the valley floor. This procedure might be used in the analysis of a landscape.

Another useful technique in analysing a surface is to use artificial raking light to illuminate a scene from directions not possible by relying on sunlight alone (Fig 30; *see* Case Study 8).

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.

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



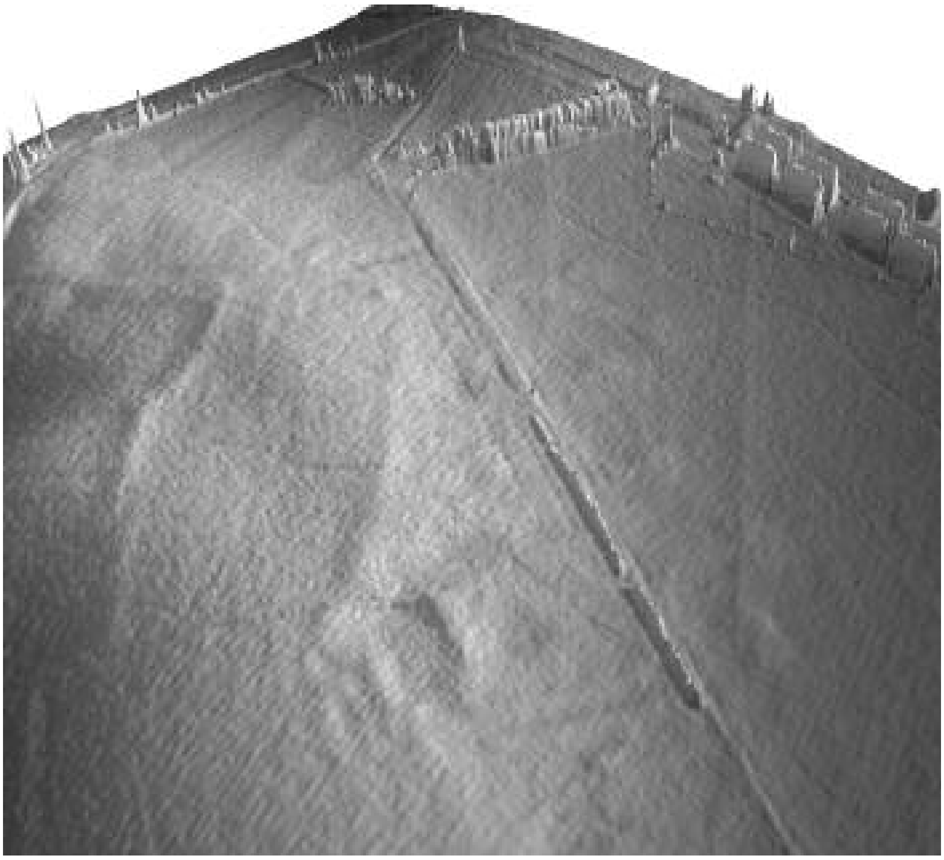
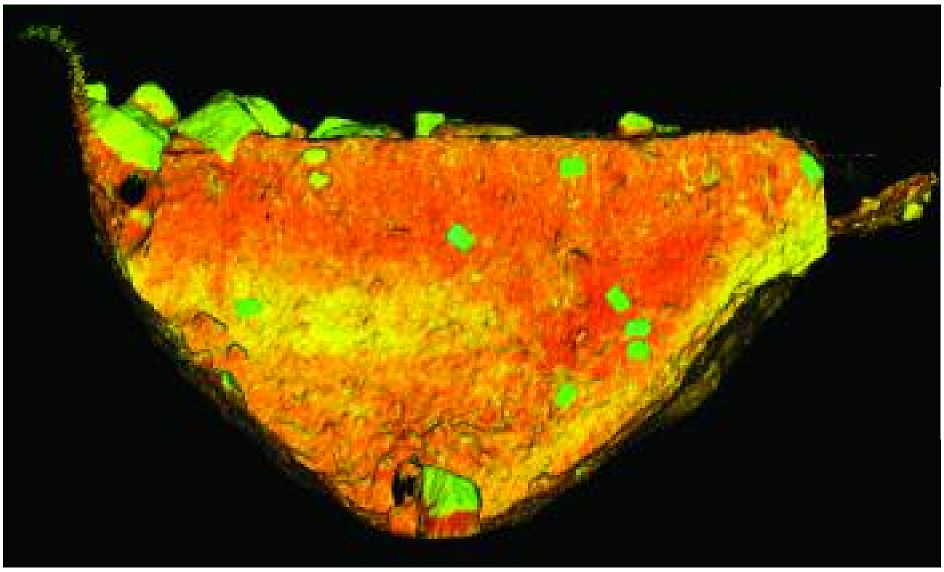


Fig 31 Elevation data from airborne laser scanning in the Witham Valley (top) and displayed with ten-fold vertical exaggeration (bottom) revealing possible early field systems to left of image (courtesy of Simon Crutchley, English Heritage, Lidar courtesy of Lincolnshire County Council – Source Environment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

This may be coupled with the use of artificial raking light (Fig 31).

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 may be



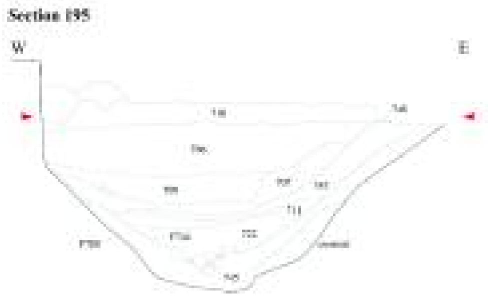


Fig 32 A laser scan of an excavated section with intensity information (left), and a stratigraphic record of the ditch made by an archaeologist on site (below) (courtesy of Newcastle University and Archaeological Services University of Durham).

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 which is seen in reality. Such information can be useful, in some cases in differentiating between slight changes in surface or material type. Figure 32 shows an example of how the intensity information from a scan of an archaeological excavation can be compared with the record made onsite.

Three-dimensional geometric models may also be used to generate high-quality still or animated scenes. Movies have been used successfully to present what would otherwise be very large data quantities 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 textures. Textural information can often help to replicate geometric detail, and reduce the need for some vertices.

5 Managing data

5.1 Reprocessing data

Data is generated at a number of stages during a laser scanning survey. In order to be able reprocess data at a later date a user should ensure that the most appropriate data is available. The following diagram (Fig 33) summarises these stages and the data they produce:

Raw observations
(As collected by the scanner)
▼
Raw XYZ
(As determined by the scanner)
▼
Aligned XYZ
(Determined by processing software/process)
▼
Processed model
(As chosen by the user)

Fig 33 Types of data arising from laser scanning.

Raw observations are not universally available, and data formats differ between manufacturers. Raw XYZ data is, 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 re-sampling (often referred to as 'decimation' when used in reference to data manipulation) of the data.

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 forms 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 purpose. 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 transfer, 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 packages. However, it can also be used to transfer ground based laser scanning data. The LAS format is currently being revised by its steering committee to Version 2.

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 you intend to use. A good general purpose format for the delivery of meshed models is the Alias Wavefront OBJ format.

The type of 'deliverable' 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's (ADS) project 'Big Data'.

5.3 Metadata

An important component of the data management process is the definition and management of metadata: 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 might be maintained for raw scan data might include the following:

- file name of the raw data
- date of capture
- scanning system used (with manufacturers serial number)
- company name
- monument name
- monument number (if known)
- survey 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* "An Addendum to Metric Survey Specifications for English Heritage – the Collection and Archiving of Point Cloud Data Obtained by Terrestrial Laser Scanning or other Methods". This document is currently available as a pdf file download from the Heritage3D website **www.heritage3d .org**, but will soon be inserted into the 2007 revision of the "Metric Survey Specifications of English Heritage" (ISBN 1 873592 57 4, published by English Heritage 2000; reprinted March 2003).

6 Helping you to decide

Asking yourself 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 you 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 your 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 would be appropriate to apply. A triangulation laser scanner could 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, although larger, might also be suitable for measurement using a triangulation scanner, although if the object is fixed in place, access to it should be considered. Alternatively, it might be suitable to use a system based on time-of-flight measurement.

At the scale of a building façade or of an entire building, measured survey using triangulation scanners would 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 scanner would be more appropriate.

For entire sites, where the topography of the site 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 be the only likely 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 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 has 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 small carvings and 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 if 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 hydraulic mast or cherry picker is possible, although care should be taken to ensure that the scanner remains stable during operation (Fig 34).

Fig 34 Laser scanning from scaffolding (courtesy of Duncan Lees, Plowman Craven Associates).

Access might be restricted on health and safety grounds, because a building is unsafe, making a survey only possible from a few locations. In an archaeological excavation, survey may 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 (is 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 section, profiles and plans. It is especially useful when access to a site makes it difficult to use conventional methods (*see* Case Study 11). The way in which laser scanning enables direct integration of the collected data on site can also help a contractor reduce the likelihood for revisits.

6.8 Budget

Although laser scanning is 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 used, it is advisable to try to ensure that it can be used in many different ways, so as to provide best possible value from its commissioning.

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 skills in providing precise survey control measurement and/or specialist skills in 3D CAD or GIS. If this is your first project, using a contractor is advisable.

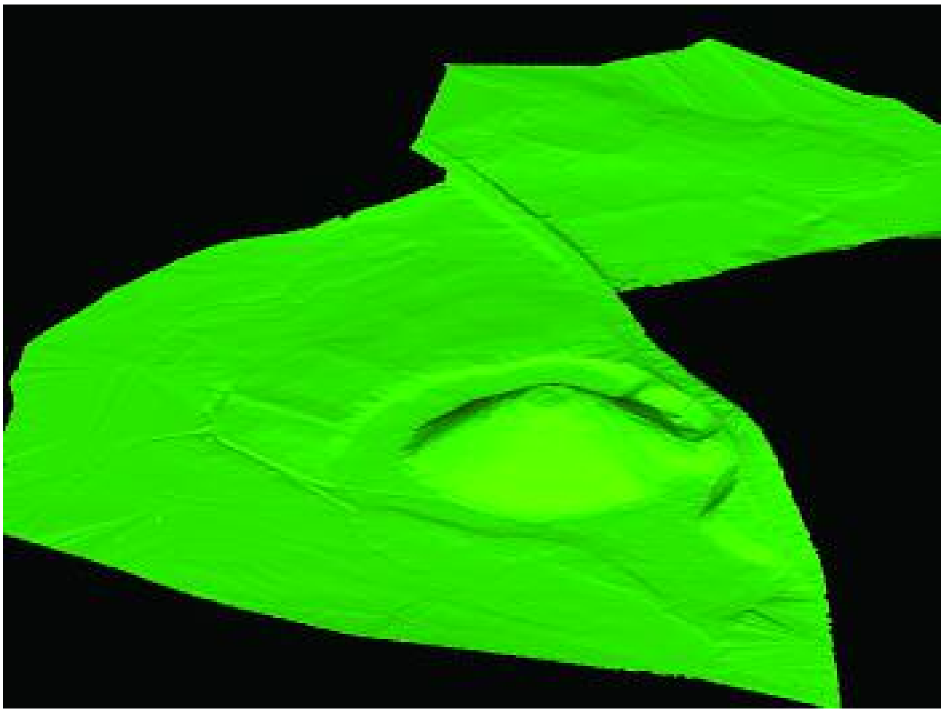
6.10 What are the alternatives?

Digital photogrammetry is the technique to which laser scanning is most compared. Photogrammetry is increasingly easy today, compared to 5–10 years ago when it generally required the use of specialist analytical instruments (Fig 35). 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 GPS (Fig 36) or a reflectorless total station survey might provide a lower-cost site survey, but over a large landscape this might not be suitable. Terrestrial 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 35 An operator using a digital photogrammetric workstation (courtesy of English Heritage).

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



7 Where to find out more

7.1 Charters and guidance

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

Overall guidance and a detailed specification for the use of recording techniques are available from the English Heritage Metric Survey Specification. Contact the English Heritage Metric Survey Team for more information (contact details are given below).

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

English Heritage Metric Survey Team, York
English Heritage
37 Tanner Row
English Heritage
York YO1 6WP
http://www.english-heritage.org.uk/server/show/conWebDoc.4143

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
http://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
http://www.rics.org/

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

7.3 Books

To date, there are no books that specifically 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. These books make some reference to the use of laser scanning:

English Heritage 2003 *Measured and Drawn – Techniques and practice for the metric survey of historic buildings*, 62 pages

Dallas, R W A 2003 *A guide for practitioners – Measured survey and building recording, Historic Scotland*, 180 pages

Böhler, W and Marbs, A 2004 *A comparison of 3D scanning and photogrammetry for geometric documentation in cultural heritage*. Fachhochschule Mainz, 86 pages (in German: *Vergleich von 3D-Scaning und Photogrammetrie zur geometrischen documentation im Denkmalbereich*).

7.4 Journals and conference proceedings

There is no specific journal for laser scanning, but many major journals that cover survey techniques and cultural heritage have, in the past, included papers on the subject:

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

The Photogrammetric Record (Oxford: Blackwell)

Journal of Architectural Conservation (Dorset: 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)

GIM International (GITC bv, Netherlands)

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

Symposia for the International Committee for Architectural Photogrammetry (CIPA). Held every two years, the Proceedings of this symposium can be found online at: http://cipa.icomos.org/index.php?id=20

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

7.5 Websites

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

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

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

The English Heritage aerial survey and investigation team – Information on the work of English Heritage's aerial survey team, including their experience of lidar, **http://www.english-heritage.org.uk/aerialsurvey**

Stonehenge laser scanning – An example of laser scanning at one of English Heritage's most well known sites, **http://www.stonehengelaserscan.org/**

i3Mainz – A good source of technical information and case studies on laser scanning equipment and application, **http://www.scanning.fh-mainz.de/**

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 includes university departments and commercial survey companies.

8 Glossary

3D Having three-dimensions, characterized 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 Archaeological Data Service, University of York

CAD Computer aided design

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 topographic model of the bare earth that can be manipulated by computer programs and stored in a grid format

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

geometric accuracy The closeness of a measurement to its true value. It is commonly described by the 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 ±3 mm (67% probable error) – sometimes referred to as repeatability.

GIS Geographical information system

GPS The global positioning system – a US satellite positioning system used to position an aircraft during an airborne survey, or used as a ground based survey technique

LAS Abbreviation for data format – .las

laser Light Amplification by Simulated Emission of Radiation: an intense light beam that produces images with electronic impulses

laser scanning From a user's point of view, a 3D scanner is any device that collects 3D co-ordinates of a given region of an object surface automatically and in a systematic pattern at a high rate (hundreds or thousands of points per second) achieving the results (ie 3D co-ordinates) in (near) real time.

LiDAR Light Detecting 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 and a vital 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 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 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 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 on subject itself

survey control Points of known location that define a local reference frame 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 device that uses a laser to measure the three-dimensional co-ordinates of a given region of an objects surface automatically, in a systematic order at a high rate in (near) real time

TIN Triangulated Irregular Network

CASE STUDY 1

Creating a 3D archive of the Upton Bishop fragment

type: non-contact recording using laser scanning
keywords: non-contact, recording, 3D, archive, laser scanning, Upton Bishop, sandstone

Introduction

In addition to photographic documentation, Upton Bishop Parochial Church Council wanted an accurate three-dimensional record of the sandstone fragment shown below. The fragment measures approximately 400mm x 200mm x 210mm and belongs to the Parish of St. John the Baptist, Upton Bishop.

Upton Bishop sandstone fragment.

Instruments and software

A ModelMaker X laser scanning system with a 70mm stripe width, mounted on a 7-axes Faro gold arm was used for data capture. Sensor-object separation was maintained at 50mm throughout. Sensor and arm calibration had an average RMS error of 0.03mm. Scanning was carried out in our studios in Liverpool. Four scanning stations were required to capture the whole object. There was no sampling during data capture. The software used to collect the data was 3D Scanners UK ModelMaker V7 beta release. Once scanning was complete, the data was 2D sampled at u = 0.2 and v = 0.2 mm using MM V7. Polyworks V8 (Innovmetric Software, Inc) was employed for data alignment, merging and post-processing. The maximum edge length parameter used during meshing was 0.2mm. Rapidform2004 PP2 (INUS Technologies, Inc.) was used for registering and merging the data from the four scanning stations together. The average maximum deviation between the data from each of the scanning stations was 0.04mm. Any areas where the Faro arm had been at full stretch during scanning were deleted, and data from another station was substituted.

Upton Bishop fragment: screenshots of 3D data.

Abnormal faces were deleted and all holes were filled manually using Rapidform2004.

Production of 3D fly-throughs in AVI format was undertaken in 3D Studio Max (AutoDesk Media and Entertainment). Photographic documentation was captured using a Minolta Dimage 5 3.3 megapixel digital camera at a resolution of 1600 x 1200 pixels, mounted on a tripod. Each image was manually white-balanced.

Why was scanning selected?

Upton Bishop Parochial Church Council wished to have a 3D archive of this important object. The Church Council wishes to improve access to this delicate and important object, while limiting handling of the piece to a minimum. Upton Bishop Parochial Church Council and other academics are attempting to learn more about the fragment; currently it is undecided whether it is Early Christian or Roman in origin. The fragment is very fragile; any handling results in some surface loss. In addition to the photographic documentation, the 3D digital model can be supplied as a set of screenshots, a fly-through or as a virtual model to a variety of interested parties worldwide. In this way the fragment can be made available to a large number of scholars and members of the public, while limiting any potential damage to this important object. A 3D virtual model enables Upton Bishop Parochial Church Council to provide the archive, with photographic documentation, to experts and interested parties to help establish the provenance of the piece. In addition, the possibility exists to create a replica of the fragment if the original is ever stolen, damaged or destroyed. An extremely accurate replica (either to scale, or to different sizes) can be made in the original material, sandstone (or alternatively, synthetic materials). The data obtained by laser scanning is used to control the tool path of a CNC (computer numerically controlled) milling machining.

What problems were encountered?

Owing to the fragile and friable nature of the surface of the fragment, handling and positioning of the piece was kept to a minimum. As the piece could not be propped up, and had to remain horizontal throughout scanning, a larger number of scanning stations than usual was required for a piece of this size. As scanning was undertaken in the studio, the data captured was exceedingly accurate. Registration and merging the separate stations did not pose any problems.

What were the final 'deliverables'?

Upton Bishop Parochial Church Council were supplied with a copy of the raw scan data (in SAB2, a 3D Scanners file, and ASCII format), as well as the completed post-processed data in STL format, photographic documentation of the originals, and metadata detailing how scanning and post-processing was undertaken. A fly-through where the object spins slowly through 360° in AVI format was also provided.

CASE STUDY 2

Recording a Norman doorway, Prestbury Church

type: triangulation
keywords: non-contact, laser scanning, doorway, architectural fragment, documentation, recording

Introduction

Prestbury Church (Cheshire) has an important Norman doorway. The doorway and surround measures approximately H 6m x W 2.8m x D 0.7m, the smallest detail to be recorded on the doorway and surround was approximately 5mm. The sandstone surface is badly weathered and very friable. We provided Prestbury Parochial Church Council with a full data set. The aim of the work was to provide an accurate 3D record of the doorway at the time of recording.

Instruments and software

A Mensi S25 laser scanner mounted on a large tripod was used for data capture. The Mensi S25 works by triangulation. Sensor-object separation ranged between 3m and 7m throughout data capture. The S25 records points across the surface in a grid in an automated fashion, once the user has determined the scan area and grid size. The average grid size used for recording the doorway was 3mm. Detailed sections were captured at 2mm, areas of less detail, such as the door and the surrounding brickwork, were recorded with a maximum grid size of 4.2mm.

The resolution of the data is dependent on the grid size determined by the operator and the accuracy of the system. The Mensi S25 has a relative accuracy of 0.619mm at an object-scanner separation of 5m, with an error of ±1.2mm. During scanning at a distance of 3m, with a grid size of 2mm, the standard deviation was recorded as 0.86mm. A calibration check was performed on the system prior to scanning and on completion of data capture, on a 999.96mm carbon fibre bar at a distance of 5m.

The measurements had an average error of 0.471mm. Data capture required 10 scanning stations and took 22 hours on site to complete. Power was supplied via a mains socket within the chapel. The scanner, associated equipment and operators were housed in a tent to protect them from the elements. Scanning could only take place in low lighting conditions or complete darkness. Recording took place in December, when the evenings are long. The data was recorded using Scanworks software (Mensi-Trimble). Polyworks V8 (Innovmetric Software, Inc.) was employed for data alignment of scanning patches and meshing. Registration and merging of the different stations and post-processing was undertaken in Rapidform 2004 SP2 (InusTechnologies, Inc).

The average shell-shell deviation during registration was 0.65mm. A small amount of manual hole filling and localised smoothing was required. In total, post-processing of the data took 35 hours. Production of 3D fly-throughs in AVI format was undertaken in 3D Studio Max (AutoDesk Media and Entertainment). Photographic documentation was captured using a Minolta Dimage 5 3.3 megapixel digital camera at a resolution of 1600 x 1200 pixels, mounted on a tripod.

Why was scanning selected?

We wished to examine the use of an S25 laser scanning system for the recording of an outdoor architectural feature. We were pleased with the data we obtained. We felt it was of good resolution and accuracy with regard to the size of the scanning area and the level of detail on the doorway and the surround.

What problems were encountered?

The S25 requires low levels of lighting to be able to capture sufficient data to record the surface. For this reason, rather than erect a very large and expensive scaffold housing around the entire scanning areas, scanning was undertaken at dusk and nighttime. The laser beam used in the S25 is in a class of laser (class 3A, according to the CDRH 21 CFR 1040 standard) that can cause damage to the eye, if one were to look directly into the beam. When the system is scanning, the beam is constantly moving and the blink reflex will protect the eye from damage. It is imperative that no one looks directly into this beam. The area in which scanning takes place was sectioned off from public access using cones and hazard warning tape. In addition, highly visible warning signs were used around the site. Despite the system being semi-automated, the equipment was never left alone. One operator was always present to ensure no one entered the scanning area, and to monitor data capture. If needed, the system has an emergency stop button that will pause data capture and shut off the laser beam. This can also be useful when wildlife gets in the way of data capture. Our team always sends two operators onto site with this piece of equipment for these reasons.

What were the final 'deliverables'?

Prestbury Church Parochial Council were supplied with a copy of the raw scan data (in SOISIC (Mensi S 25 file and ASCII format), as well as the completed post-processed data in STL format, photographic documentation of the original and an AVI flythrough of the doorway.

The Norman doorway: detail, 3D screenshot of data.

CASE STUDY 3

3D recording of three petroglyphs on Rombald's Moor, West Yorkshire

type: arm-mounted triangulation scanner
keywords: 3D recording, documentation, in-situ, laser scanning, rock art, petroglyphs, virtual images, digital archive, Rock Art Pilot Project, Rombald's Moor

Introduction

As part of the English Heritage Rock Art Pilot Project (1999), laser scanning as a method of documenting rock art in the field, was examined. The petroglyphs studied are located on Rombald's Moor in West Yorkshire. The areas scanned were approximately 1.2m ? 0.5m in size. Laser scanning was found to be a good technique for the 3D non-contact recording of rock art. The equipment is suitable for use in the field – even in remote locations.

The petroglyphs on Rombald's Moor, West Yorkshire.

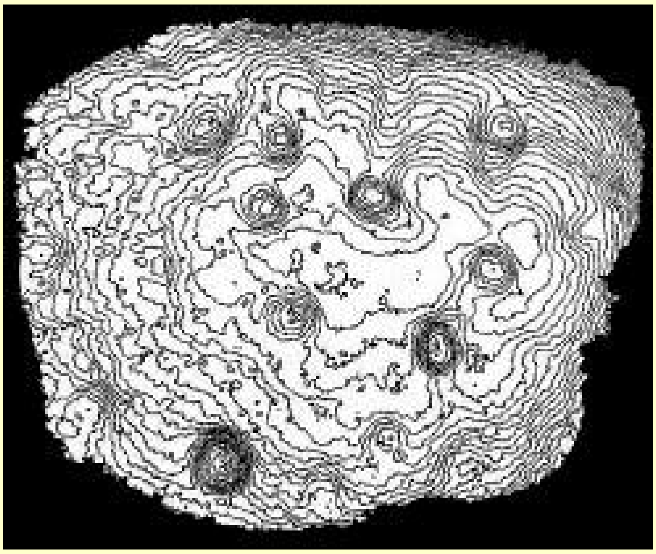
The data obtained documented the petroglyphs to a high level of detail. Importantly, the results were not subjective to lighting conditions at the time of data capture. Indeed, once the data had been post-processed, and was examined under varying lighting conditions, a distinct wear pattern was located on the surface of one of the rocks. This pattern had not been discernable from photography, nor with the naked eye. The results of laser scanning can be exploited in a wide variety of imaging formats, providing a flexible digital archive. Images of contour maps of the surfaces and a scale replica in polyurethane were also produced from the data.

Instruments and software

A ModelMaker H laser scanner (3D Scanners UK) mounted on a six-axes Faro silver arm was used to record the petroglyphs. A sensor with a 40mm stripe width was used, and the scanner recorded at a rate of twelve stripes per second. Stripe-stripe separation is dependent on the speed at which the sensor is moved across the surface by the operator, and ranges from 4mm–0.2mm.

The petroglyphs were recorded with high accuracy, hence with a slow scanner speed, producing a dense point cloud. Data was captured using ModelMaker V1 software. Meshing and post-processing was also carried out in ModelMaker software. All data was checked on site.

Areas that may have been missed during data capture were easily highlighted and ensured as complete a data set as possible was recorded. The raw point cloud was also crudely meshed on site to check the quality of the scan data. ModelMaker V1 was used to create a contour map of the individual rocks. Each rock art panel required 3–4 hours to scan, including the time it took to move the equipment and prepare it for data capture.



3D contour map of one of the rocks.

Laser scanning on Rombald's Moor.

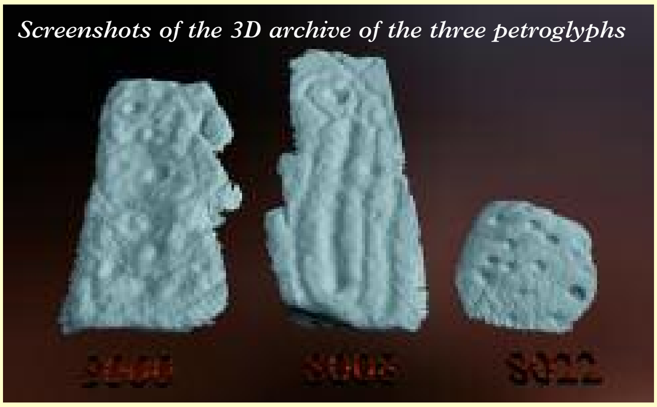
Why was scanning selected?

Commonly used 2D techniques such as sketching, rubbing, and photography employed to record rock art are subject to lighting conditions. Moreover, they suffer inaccuracies owing to the difficulty of rendering a 3D surface in 2D. Close range photogrammetry, while providing a 3D archive, is still subject to the lighting conditions at the time of recording. Moulding and casting techniques, while both 3D and non-light subjective, can damage the weathered surface of a petroglpyh.

Non-contact recording using laser scanners provided a solution to all of these problems. In addition, by fixing datum points close to the rock panel it is possible to rescan the rock at a later date. The two data sets can then be compared to measure and monitor any changes or decay on the surface of the petroglyph.

What problems were encountered?

The ambient light levels on the moor were too bright for laser scanning (scanning was undertaken during summer). As this was anticipated, a small tent was erected over the site.



Screenshots of the 3D archive of the three petroglyphs

The tent suitably reduced light levels to enable data capture. Calibration of the equipment on site was difficult. There was a lack of solid surfaces to mount the geometric cube used for calibration. It was necessary to calibrate the arm off-site, move the equipment with care, and check the calibration on completion of scanning, off-site. In this way it was possible to ensure that calibration had remained within specification throughout data capture.

What were the final 'deliverables'?

The raw data was provided in CTA (3D Scanners file) and ASCII format. The post-processed data was provided as STL files, and the 3D contour maps were delivered in IGES format. In addition, the data obtained by laser scanning was used to produce a scale replica of one of the rocks in lightweight polyurethane using 3-axes cnc (computer numerically controlled) machining.

CASE STUDY 4

Non-contact 3D recording and replication of medieval Graffiti at the Tower of London

type: arm-mounted triangulation scanner
keywords: non-contact, laser scanning, replication, CNC machining, exhibitions, Historic Royal Palaces, Medieval graffiti, Arundell, Dudley

Introduction

In 2003 Historic Royal Palaces re-designed the exhibition space within the Beauchamp Tower at the Tower of London. The Medieval graffiti carvings in the upper room were to be replicated to improve visitor access. Owing to the fragile surface of these carvings traditional moulding techniques could not be used.

The Dudley carving: Beauchamp Tower.

We employed non-contact 3D recording using laser scanners to create digital 3D models of the carvings. The data produced in this way can be used to control the tool path of a robotic milling machining. From our scan data, scale replicas were produced using 3-axis CNC (computer numerically controlled) machining. The replicas were installed in the new exhibition in December 2003 and greatly improve visitor access to these important carvings. The original graffiti remains on public display, behind sheets of glass for protection, in the upstairs room of the Beauchamp Tower. Visitors can explore the graffiti inscriptions from the replicas prior to visiting the upstairs area, and are encouraged to touch the replicas.

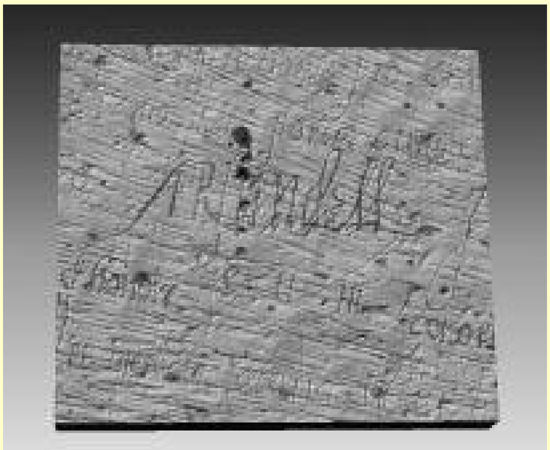
Instruments and software

A ModelMaker X laser scanning system with a 70mm stripe width, mounted on a 7-axes Faro gold arm was used for data capture. Sensor-object separation was maintained at 50mm throughout. Arm calibration had an RMS error of 0.039mm and sensor calibration had an RMS error of 0.029mm. Sensor checks, both in the studio and on site at the Beauchamp Tower, had RMS error values of 0.04mm. One scanning station per carving was required and there was no sampling during data capture.

The software used to collect the data was 3D Scanners UK ModelMaker V7 beta release. Once scanning was complete, the data was 2D sampled at u = 0.2 and v = 0.2 mm using MM V7. Polyworks V8 (Innovmetric Software, Inc) was employed for data alignment, merging and post-processing. Rapidform2004 PP2 (INUS Technologies, Inc) was used for post-processing and preparation of the data for CNC machining.

The ModelMaker X laser scanning system.

Production of 3D flythroughs in AVI format was undertaken in 3D Studio Max (AutoDesk Media and Entertainment). Photographic documentation was captured using a Minolta Dimage 5 3.3 megapixel digital camera at a resolution of 1600 x1200 pixels, mounted on a tripod. Each image was manually white-balanced. The glass protective glass sheets over the graffiti were removed prior to data capture.



The Arundell carving: screenshot of 3D data.

Why was scanning selected?

Owing to the friable nature of the surface of the carvings, the conservation department at Historic Royal Palaces had deemed the carvings too delicate to take moulds from the originals.

What problems were encountered?

We had to use a collapsible lightweight tripod due to the narrow staircase that provided access to the scanning site. In addition, we were unable to attach or glue the tripod to the floor in any way. The floor is too the delicate. Moreover, we were unable to totally exclude movement of the floor. Despite the room being closed to members of the public for the duration of data capture, we were not allowed to remain alone during scanning at this military site. Consequently, we observed higher than normal movement during scanning, particularly between stripes. We were able to re-align the stripes using Polyworks to within 0.2mm.

The scan data of the Arundell carving exhibited some unusual features. Scanning features that are best visually described as 'pixilation' along some of the sharp edges of the inscription were observed in the 3D model. This could not be explained by a lack of data. It appears to be due to the nature of the patination of the letters (the black and white paint in the inscription), combined with the direction of the stripe during scanning. Possible movement of the wooden floor while scanning may also have led to errors in the data. The most pronounced example of this was observed on the A of Arundell.

What were the final 'deliverables'?

Scale replicas of each carving were milled in high-density cast resin (Ebablock 1200 f+f, Denaco UK) using three-axes CNC machining. Minimal hand finishing of the replicas by our sculpture conservators was required to remove machining marks and 'pixelation' in small areas on the Arundell carving. Chisels, rifflers and scalpels were used. During patination of the replica graffiti, alkyd paints were applied using brushes, cloths and sponges. The surface was finished with a matt varnish.

In addition, Historic Royal Palaces were supplied with a copy of the raw scan data (in SAB2, a 3D Scanners file, and ASCII format), as well as the completed post-processed data in STL format, photographic document-ation of the originals and the replication process and metadata detailing how scanning and post-processing was undertaken.

The replicas installed in the new exhibition space at the Beauchamp Tower, Tower of London.

CASE STUDY 5

Copying Caligula

type: arm mounted triangulation scanner
keywords: non-contact, laser scanning, 3D virtual model, replication, replica, CNC-machining marble, polychrome sculpture, Caligula, colour reconstruction

Introduction

In the collections of the Ny Carlsberg Glyptotek (Copenhagen, Denmark) is a marble bust of the Emperor Caligula. The sculpture was probably carved between 39 and 41 AD. Originally such sculptures were painted (polychrome) and this piece has traces of the original polychromy remaining. Roman marble sculptures retaining their original polychromy are exceedingly rare. The curators and conservators in Denmark wished to study the pigments to determine their exact composition and then reconstruct a possible colour scheme on a replica object. Their intention was to display the original and a painted replica side-by-side. Due to the fragile pigmented surface of the bust, traditional moulding techniques could not be used. We employed non-contact 3D recording using laser scanners to create a digital 3D model of the sculpture. The data produced in this way can be used to control the tool path of a robotic milling machining. From our scan data, a full-scale replica in marble was produced using 5-axis CNC (computer numerically controlled) machining. The re-pigmented replica was displayed, next to the original, in exhibitions in Munich, Copenhagen, and Rome during 2004 and 2005.

Instruments and software

Data capture took place in our studio (Liverpool, UK) using a Modelmaker H laser scanning system. The sensor has a 40mm stripe width and was mounted on a 6-axes Faro silver arm. Sensor-object separation was maintained at 100mm throughout. Arm calibration and sensor calibration were within specification. One scanning station was required and there was no sampling during data capture. The software used to collect the data was 3D Scanners UK Modelmaker V2 beta release. During data capture, two million points were captured. Once scanning was complete, the data was meshed using MM V2. Rapidform2002 (INUS Technologies, Inc.) was used for post-processing and preparation of the data for machining.

Caligula: screenshots of 3D data (left – raw data, right – completed model).

The replica during CNC machining.

The final model comprised 2.3 million polygons. The raw data is stored as CTA, SAB2 (MM file formats) and ASCII files. The completed model is stored in STL format. Production of 3D fly-throughs in AVI format was undertaken in 3D Studio Max (AutoDesk Media and Entertainment). Photographic documentation was captured using a Minolta Dimage 5 3.3 megapixel digital camera at a resolution of 1600 x 1200 pixels, mounted on a tripod. Each image was manually white-balanced. A new block of Carrara marble was sourced from Italy. A five axes CNC machine was used to mill the replica into a new block of Carrara marble.

Why was scanning selected?

Taking a mould from the original sculpture and casting a replica could not be considered because of the delicate nature of the surface. The taking of a cast would in all probability damage the pigmentation. In addition, this process would result in a plaster or other synthetic material replica, not a marble copy. The curators of the project wanted to examine a colour reconstruction onto the original material – marble. A sculptor copy-carving the bust may have led to some element of re-interpretation of the piece, no matter how minor or unintentional. For these reasons replication by non-contact recording and replication was required.

What problems were encountered?

The copying Caligula project was one of the first we had undertaken that involved the machining of a full bust into marble. Until this time we had only produced reliefs by this process. Initially, the replica was to be machined by a university spin-off company. Prior to machining starting, the company folded and was unable to fulfil the contract. Finding a new sub-contractor was a major task. In addition, the new subcontractor had to develop new expertise to use their equipment to machine into marble. These complications created a delay in the delivery of the bust; however, colour reconstruction was completed in time for the replica to be installed in the exhibition before opening.

What were the final 'deliverables'?

A full-scale marble replica of the bust was supplied to the NY Carlsberg Glyptotek, Copenhagen. The replica required twelve hours of hand finishing by our sculpture conservators. A point chisel and a flat bladed chisel were used to sharpen facets in the hair, a drill was used to deepen the mouth, and a dremmel (small drill) was used to deepen the ears. A fine abrasive paper was employed to remove tool markings from machining from the nose and face. To help the sculpture conservator during this process, a thin watercolour wash was applied to the surface of the replica, as it is difficult to see the details on a new 'clean white' marble sculpture clearly.

Caligula original (right), and marble replica (left) before pigmentation added.

Colour reconstruction on the marble replica was undertaken by the Doerner Institute, and the Glyptotek, Munich. The reconstructed replica and the original were displayed side-by-side in Munich, Rome and Copenhagen as a part of the exhibition, 'ClassiColor', examining colour in Greek and Roman Classical sculpture.

3D Non-contact recording of an Anglo-Saxon cross, Prestbury

type: triangulation
keywords: 3D, non-contact, recording, laser scanning, digitisation, 3D record, Minolta V1900 laser scanner, digital archive, Anglo-Saxon Cross, Prestbury Church

Introduction

In the churchyard of Prestbury Church stands an important Anglo-Saxon Cross, thought to mark the arrival of Christianity in the North West of England. The sandstone cross measures 940mm x 400mm x 240mm, the surface is weathered and some green moss obscures the upper east face.

The original location of the cross is unknown; however, it was previously sited inside the church. The cross is highly decorated with intricate patterns. There are clearly sections missing, particularly between the three sections it is now in, discernable by gaps in the pattern either side of fills holding the piece together. Prestbury Parochial Church Council wanted the cross accurately recorded prior to conservation work and possible re-siting.

Anglo-Saxon cross, Prestbury.

Instruments and software

A Minolta VI 900 laser scanning system was used for data capture. The instrument was mounted on a tripod, and set to fine mode. A middle lens was used throughout data capture. Sensor-object separation was maintained at approximately 1000mm. The exception to this scanning offset was the very top of the cross, which had to be recorded from a distance of 2000mm. The calibration of the system was checked using a 100mm calibration board, prior to scanning and again on completion of data capture. The scanner was working to within the manufacturer's specification. A tent was erected over the scanning area to reduce the ambient light levels. This ensured we obtained the best data possible.

Scanning took a total of 6.5 hours and we collected 121 frames. The frames were saved directly as meshes to a flash card connected to the scanner. We undertook rough registration on- site to ensure that we had covered the whole surface, and to ensure that the data recorded was of a high quality. Rapidform2004 PP2 (INUS Technologies, Inc) was used to register and merge the individual frames into a coherent model. The average shell-shell deviation for this process was 0.3mm. large areas of overlapping data were deleted prior to merging, with the best data being chosen wherever possible. Rapidform 2004 SP2 was employed for the post-processing of the data, which entailed cleaning polygons and filling small holes manually. A small amount of localised smoothing was required in areas where the data was noisy. This was in the most part where there are very dense moss patches, *c* 2cm^2 in area. The data was decimated by 50% on bringing the individual frames into Rapidform 2004 SP2 prior to registering and merging, and the final model was decimated again by 50% at the end of the post-processing procedure. The final model contained approximately 3.5 million polygons. Production of 3D flythroughs in AVI format were undertaken in 3D Studio Max (AutoDesk Media and Entertainment). Photographic documentation was captured using a Minolta Dimage 5 3.3 megapixel digital camera at a resolution of 1600 x 1200 pixels, mounted on a tripod. Video footage of the cross in its current location (including the immediate surroundings and the scanning process) was recorded using a Sony 3CCD DVCAM.

Scanning the cross.

Why was scanning selected?

A highly accurate record of the surface of the cross was required prior to possible dismantlement, conservation and re-siting. Taking a mould of the object was not an option in this case due to the friable nature of the sandstone surface. An accurate 3D model was also required in case it is decided at a future date to create a highly accurate replica of the cross. Laser scanning is an ideal technique for this.

What problems were encountered?

The presence of moss in some localised areas meant that we could not record the stone surface underneath as accurately as the most of the surface. However, these areas are small, and the data clearly shows the form of the pattern in these areas.

What were the final 'deliverables'?

All raw data was supplied in CDM format. This comprises the 121 frames and was provided with a data log that provides information about each frame. The completed data was supplied in STL format. Photographic documentation was provided in JPEG and TIFF formats. In addition, screenshots of the completed data in JPEG format, and AVI flythoughs of the 3D cross both textured and un-textured were supplied in AVI format.

Prestbury Anglo-Saxon cross screenshot of 3D data.

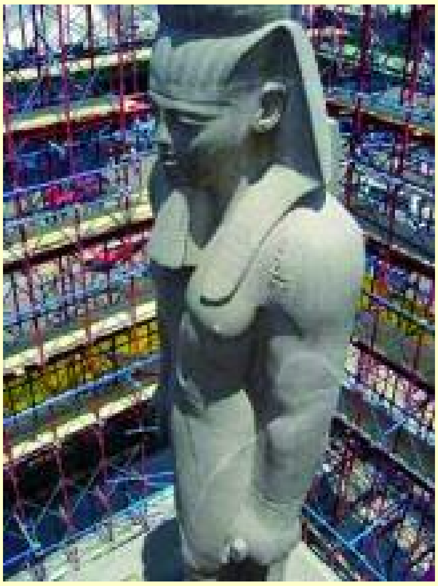
CASE STUDY 7

A moving story - The Ramesses II scanning project

type: medium range time of flight
keywords: statue, Cairo, structural analysis

Introduction

For the past 50 years, a colossal red granite statue of Ramesses II, one of the mightiest pharaohs of the 19th Dynasty of Egypt, has languished in downtown Cairo's Ramesses Square. The statue has been deteriorating badly from pollution generated by the traffic that clogs the three major thoroughfares that meet at the square, and from mainline and underground trains. Some fear that the excessive vibrations from this traffic may also affect the statue in due course. The Egyptian authorities have decided to move the statue to the Grand Egyptian Museum, which is being planned for the Giza Plateau, and should be built by about 2010. Survey was required to provide a permanent, accurate record of the statue and to provide the data necessary to move the massive monolith safely. (This move has now taken place: *see* **http:// news.bbc. co.uk/1/hi/world/ middle_ east/ 5282414.stm**)


Statue of Ramesses surrounded by scaffolding.

Duncan Lees of Plowman Craven & Associates (PCA) – one of the world's largest geomatics companies to specialise in 3D survey and heritage projects – undertook the work, organised by Lon Addison of the University of California at Berkeley and UNESCO, with colleagues Björn Van Genechten from the Catholic University of Leuven in Belgium and Dr Tariq Al Murri.

Instruments and software

The survey used a Leica Geosystems HDS2500 laser scanner to create an accurate 3D computer model of Ramesses' effigy. They used the scanner together with a range of other image-based 3D data collection techniques, including photogrammetry. Leica's Cyclone software was used for pre-processing and registration of the scanning datasets. The registered point cloud was exported as an ASCII .xyz file and meshed in Raindrop Geomagic. Hole filling and checking of the data was undertaken in Geomagic and Cyberware Cyslice.


Registered point cloud of upper part of statue.

The mesh data was exported in .stl, .obj and .ply formats. Rhinoceros software was used to produce automatic vertical and horizontal cross-sections through the statue and a contour map of the surface. Leica CloudWorx and Microstation were used to add detail to linework elevations of the hieroglyphs that adorn the statue.

Why was scanning selected?

Traditional survey techniques such as digital data capture using a total station theodolite or photogrammetry rely upon the identification of edges by the surveyor or photogrammetric plotter. The statue of Ramesses II, as with many other statues and structures, is an organic, irregular shape characterised by the presence of many surfaces and few hard edges or vertices. Laser scanning is fundamentally a surface data collection technique and so was ideally suited to recording the intricate structure of the statue in a timely and cost-effective manner.

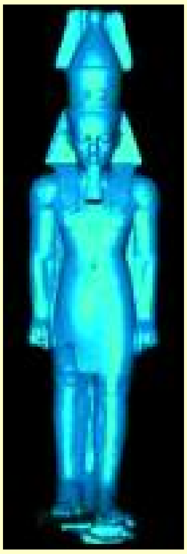

Meshed data set depicting intricate detailing of statue.

What problems were encountered?

Temperatures during the working day exceeded 45° centigrade, although the field team seemed to suffer much more than the equipment. The statue was surrounded by scaffolding, which proved a far from ideal base for the scanner. The HDS2500 utilised was mainly situated on the scaffolding walkways, rather than on a tripod, to minimise the movement of the scanner.

What were the final 'deliverables'?

The mesh model was delivered to the client in a number of file formats. 3D CAD drawings in AutoCAD, and Microstation of the four elevations of the statue, with the hard detail outlined and contours created, were also produced. The survey resulted in a full record of the statue in its minutest detail, including all of the joints, visible fault lines and cracks. The mesh will be used for a structural analysis of the component pieces of the statue before it is dismantled and moved, allowing calculations of the weight and volume of the statue to be made. This in turn will supply the necessary information needed to create a purpose-built secure cradle to hold the mighty statue. As it was a commercial contract the data is held by the client rather than by a heritage organisation.


Completed 3D model of statue.

CASE STUDY 8

Recording prehistoric rock art by photogrammetry and laser scanning

type: photogrammetry, triangulation laser scanning
keywords: low cost, photogrammetry, Minolta laser scanner

Introduction

Prehistoric rock art comprises abstract 'cup and ring' marks found across many regions of northern Britain. Often, the rock surface also appears to form part of the overall design. Traditionally, rock art has been recorded using 2D techniques, particularly photographs and rubbings. Although adequate for basic documentation, both techniques are limited in terms of the level of detail and objectivity that can be achieved, and, in the case of repeated rubbings, can be harmful to the rock surface. In addition, the limitations of the techniques can mislead interpretation.

The Northumberland and Durham Rock Art Project, funded by English Heritage between 2004 and 2006, is developing a toolkit to enable non-intrusive digital recording of the rock art and rock surface. The project has recruited and trained about 50 volunteers from the local community and the methodology has been specially designed for them to use with ease. The core aim of the project is to use this toolkit to document all engraved panels (currently about 1500) in this region and to produce a comprehensive database, accessible to the general public via a website. For this 'baseline' recording, 2D data are captured using GPS, digital photographs and specific recording proformas. 3D data are captured using stereo photography. High-resolution recordings of select panels have also been made using laser scanning.

Instruments and software

All volunteers are using Nikon Coolpix E5400 digital cameras. The photogrammetry methodology has been specifically designed for the project's baseline recording by Paul Bryan of English Heritage, with assistance on camera calibration provided by Dr Jim Chandler of Loughborough University. Working at a focus range of 1.5m, the level of detail that can be recorded using this approach is approximately 2–3mm. The results are principally being processed through Pl-3000 'Image Surveying Station' software produced by Topcon. It is hoped that some of this processing will eventually be done by the volunteers themselves, following training in December 2005. Laser scanning of five selected panels was performed by Archaeoptics Ltd using a Minolta VI 900 scanner and processed through Demon software. The level of detail selected for this project was 0.5mm (although the system offers a resolution of 0.17mm).

Why was scanning was selected?

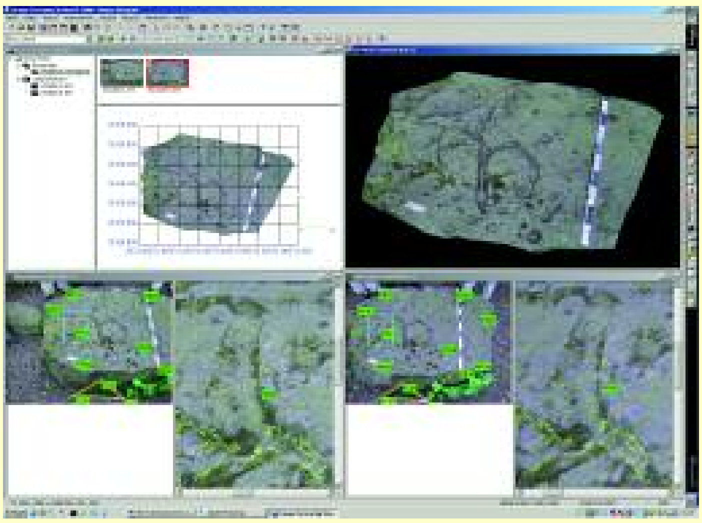
The photogrammetric technique developed for this project is user friendly, cost effective and time efficient. For a monument type such as this, where the carved stones are relatively small, prolifically scattered and often physical isolated, these are crucial issues. Accessibility is also important, and the equipment required can easily be carried by one or two people over considerable distances. These attributes make the technique highly suited to the volunteer-led baseline recording part of the project. In contrast, laser scanning is relatively expensive and requires specialist equipment and expertise both in fieldwork and in the processing stages. In this instance, it is ideally suited for high-resolution recording of a limited selection of panels.

What problems were encountered?

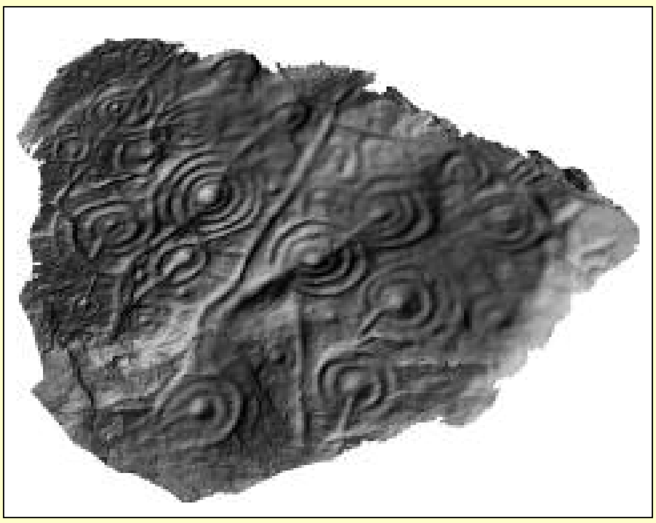
The stereo photography is still in a trial phase, but the main issues noted so far have been, first, to engage volunteers of diverse ages and abilities with the unfamiliar methodology. There has been a mixed response initially, with immediate take-up by some and considerable reticence by others. We believe that this issue will be surmountable through a cycle of repeated trial and feedback.

The second issue is the weather and light conditions, Evenly lit images, using natural light, are preferred to the more traditional 'raking-light' approach, to improve processing results. Rain has also disrupted several recording sessions.

In terms of processing, the principal problems encountered to date relate to calibration and resolution of the chosen Coolpix



Topcon's PI-3000 software was used to create digital models.



A laser scan of Ketley Crag Rock Shelter.

5400 cameras. To enable 3D measurements to be made, accurate to 2–3mm, a precise focal length is required, along with distortion information for the camera lens. So as not to over-complicate the site work for the volunteers it was decided to calibrate at only one focus setting – 1.5m. For rock panels of approximately 1m ? 1m this is a suitable compromise between coverage and detail, but for smaller panels a shorter focus setting would be useful to allow closer-in stereo-photography. Also the 5400 camera uses a CCD with an effective 5.1 megapixels. This resolution is more than adequate for general usage but can limit the processing of areas where the carved detail is less perceptible in even, natural light. How to satisfactorily record larger panels, greater than 1m x 1m, without resorting to fixed survey targets, is still an issue for the project.

What were the final 'deliverables'?

The initial results of the stereo photography have been most promising. Supplied as orthophotographs (jpegs) and surface models (currently .dxf as no .obj output is provided by PI-3000) they provide a detailed, objective record of the engravings and surface topography of the host rock. These can be viewed and manipulated at will, allowing examination of, for example, the degree and nature of lichen cover, the relationship between the carvings and erosion patterns of the rock surface, and the relative depth of the engravings. While some detail is omitted owing to the level of resolution, the information captured using this technique has considerable potential for enhancing our understanding of the rock art and evaluating its condition.

Finally, the exciting opportunities for public presentation represented by 3D data are most welcome in this context where we have, on the one hand, low public awareness, and on the other, very visual but often inaccessible monuments.

CASE STUDY 9

Leasowe Man's Skull: 3D laser scanning, digital reconstruction and non-contact replication

type: 3D laser scanning, digital reconstruction and non-contact replication.
keywords: non-contact recording and replication, 3d laser scanning, digital reconstruction, selective laser sintering, Leasowe Man, facial reconstruction, skull

Introduction

In 1863 workmen near Leasowe Castle in Wirral, Merseyside, found a skeleton. The skeleton has been scientifically dated, and the remains are the only known Romano-British skeleton from Merseyside. The remains are now in the collections of the Natural History Museum, London, but during the summer–winter of 2005 were on display in the 'Living with the Romans' exhibition at the Museum of Liverpool Life (NML). As a part of the exhibition, a full facial reconstruction from the skull was undertaken. The skull is in three parts: the cranium, and the upper and lower jaws.

The skull was scanned using a 3D laser scanner and the resulting data post-processed by Conservation Technologies, NML. The completed files were sent to the University of Manchester's Unit of Art in Medicine for digital reconstruction.* During this process, missing sections in the nasal and eye-socket areas were re-built. The bones of the upper jaw had previously been wired together in the wrong position, and this was corrected. During digital reconstruction, the upper jaw and the cranium were merged, leaving two pieces: the skull and its lower jaw. The data was then returned to us at Conservation Technologies, where we prepared the reconstructed data for use in replica production.

Scanning of the lower jaw fragment with ModelMaker X laser scanning.

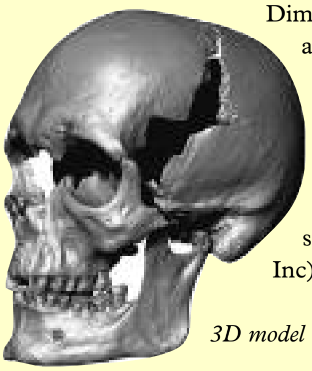
Two replicas of the digitally reconstructed pieces were produced by selective laser sintering. One replica went to Dr Caroline Wilkinson, a facial anthropologist at the University of Manchester, to be used in the creation of a full facial reconstruction, including skin tissue and hair. The second replica of the reconstructed bones was placed in the 'Living with the Romans' exhibition, where it is displayed with the original skull (as a part if its skeleton). The full facial reconstruction joined the exhibition in early September 2005.

Instruments and software

Scanning was carried out in our studios in Liverpool using a ModelMaker X laser scanning system with a 35mm stripe width, mounted on a 7-axes Faro gold arm. Sensor-object separation was maintained at 50mm throughout data capture. Sensor and arm calibration had an average RMS error of 0.032mm. We required three scanning stations for the cranium, and two each for the upper and lower jaws.

There was no sampling during data capture. The software used to collect the data was 3D Scanners UK ModelMaker V7 beta release. Once scanning was complete, the data were

2D sampled at u = 0.2 and v = 0.2mm using MM V7. Polyworks V8 (Innovmetric Software, Inc) was employed for data alignment, merging and post-processing. The maximum edge length parameter used during meshing was 1mm. Rapidform2004 PP2 (INUS Technologies, Inc) was used for registering and merging the data from the different scanning stations together. The average maximum deviation between the data from each of the scanning stations was 0.05mm. Abnormal faces were deleted and all holes were filled manually using Rapidform2004 PP2. A small amount of localised smoothing was required using the paint tool. Production of 3D fly-throughs in AVI format was undertaken in 3D Studio Max (AutoDesk Media and Entertainment). Photographic documentation was captured using a Minolta Dimage 5 3.3 megapixel digital camera at a resolution of 1600 x 1200 pixels, mounted on a tripod. Each image was manually white-balanced. Digital reconstruction of the skull was undertaken using Phantom hardware and Freeform software (SensAble Technologies Inc) at the University of Manchester.*



3D model of the digitally reconstructed skull.

Why was scanning selected?

The remains are exceedingly friable. There was no way a cast could be taken of the skull to be used for the facial reconstruction of Leasowe man.

What problems were encountered?

The digitally reconstructed data files were exceedingly large, contained much excess data, and had lost some texture on the surface of the objects. This was a function of the software only, and was in no way related to the digital reconstruction. To maintain as much textural detail as possible, and to create a smaller file, we combined the reconstructed and original files (removing the worst areas) to obtain the best data around the reconstructed areas, which were not affected by this problem, as they were created in the software rather than imported into it. Additionally, some areas of the cranium were too thin for the laser sintering process (replication). The replica would have been so fragile it would have been extremely difficult to handle. Therefore, we added an offset to the cranium of 3mm.

What were the final 'deliverables'?

A replica of the digitally reconstructed skull was supplied the University of Manchester, for use in the creation of a full facial reconstruction of Leasowe man.* Another replica of the digitally reconstructed skull is on display in the 'Living with the Romans' exhibition at Museum of Liverpool Life, NML.

Animated 'fly-throughs' of the digitally reconstructed skull were created by Conservation Technologies and have been used to generate public interest in the remains and the exhibition on the National Museums Liverpool website. Raw scan data in sab2 (3D scanners file) format, raw and completed mesh files in STL format, photographic documentation in Tiff and JPEG format, the digital reconstructions in CLY (Freeform file) and STL file format, animated fly-throughs in AVI, and project metadata, are stored at National Museums Liverpool, in line with current data storage guidelines.

CASE STUDY 10

Going underground: surveying a Grade 1 listed grotto

type: time-of-flight/phase comparison laser scanning
keywords: cave survey, restoration project

Introduction

The grotto is situated within the grounds of Ascot Place in Berkshire. As you look at the rock formation from across the lake it is difficult to believe that it is a man-made structure and that it is more than 200 years old. Once you enter the grotto, built *c* 1770, you see why it is now a Grade 1 listed building. The grotto has a series of tunnels leading into domed caverns. The walls are lined with flints and foundry slag and, in the caverns themselves, false wooden stalactites covered in lime plaster and gypsum hang in geometric patterns from the ceiling. Although the grotto is complete it is in need of extensive restoration and remedial works to stabilise the structure. HGP Conservation had no existing drawings or records to work from and a detailed survey was essential before any works could commence.

View of the grotto from across the lake.

Instruments and software

A basic topographic survey of the main outline of the structure was carried out while creating a looped traverse around, over and through the inside of the grotto, to provide control stations from which the scanner targets could be observed. Prior to surveying, it was necessary to get the exterior of the grotto cleared of the majority of the weeds and light foliage covering the structure and the laurel bushes were trimmed at the bottom to give 0.5m of clear space for scanning of the ground surface.

The exterior of the grotto from the rear appears as a series of stone steps spiralling up the grassy mound. The front of the grotto is a series of rocky cave entrances about a metre back from the lake edge. To be able to scan the exterior it was necessary to scan from a large number of locations, from both short-range and from across the lake at a distance of 50–60m. The exterior was scanned with a Leica-Geosystems HDS2500 laser scanner. Approximately 120 scans were collected to provide coverage over the whole of the exterior of the grotto and adjoining waterfall. The interior was a different story, as the size of the chambers and the passages meant that the scanning distance was between 0.5–5m. The smallest brick chamber is in fact only 1.5m in diameter. Therefore, we decided to use the Z+F Imager scanner to complete the interior, as its characteristics are best suited to these short ranges.

Scan cloud of the grotto exterior.

The survey of the exterior was processed using standard survey methods and augmented with detail extracted from the external scan data using Cloudworx for AutoCAD to create a detailed topographic survey of the exterior of the grotto. Internally, using Cloudworx, a horizontal section was cut through the scan data at a height of *c* 1m above ground, to give a wall line. All detail, including the floor patterns, water features and seats below this point were drawn to create a floor plan of the grotto. Main ceiling features were added, including all openings, arches and stalactites.

Why was scanning selected?

Laser scanning was the ideal technique to survey this extraordinary organic structure. It has provided a unique way for the people that need to work with the data to work with the survey directly and also to obtain a true three-dimensional understanding of its construction. The renovation of the grotto will take a long time and the scan data will be invaluable throughout this process as well as providing a permanent archive.

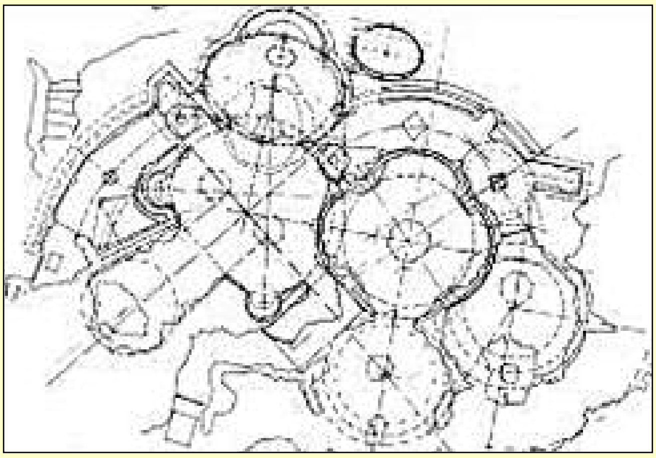
What problems were encountered?

The size of the chambers and passages meant that the internal scanning distance was between 0.5–5m, yet externally the distance was up to 60m, as on the lake side it was necessary to scan from across the lake. It was also impossible to scan into every nook and cranny but the coverage achieved was more than ample for the task.

The cramped working conditions in the interior of the grotto.

What were the final 'deliverables'?

The client was provided with a provisional copy of the floor plans so that a number of vertical sections through the structure could be chosen. This was the first time that anyone had an accurate plan showing the layout of the grotto. Five primary sections were then drawn through the grotto internally and externally. Using the survey and with careful analysis on site, it has been possible for the exact layout of the brick structure hidden behind its covering to be fully determined. The architects and engineers are continuing to analyse the cloud data themselves using Pointools View and Cloudworx software. Now the restoration programme is beginning, additional work on scanning the adjoining cascade is being carried out and 'stone by stone' elevations of the exterior and cascade are being drawn from the scan data.



Floor plan of grotto.

Thanks are given to Michael Underwood of HGP Conservation for his help with this article.
Images created using Pointools View.

CASE STUDY 11

Surveying industrial archaeology: scanning Lion Salt Works, Marston

type: time-of-flight/phase comparison laser scanning
keywords: industrial archaeology, restoration project

Introduction

The Lion Salt Works in Cheshire is the last surviving open pan salt works in the country and was recently upgraded from a Grade II listed building to a Scheduled Ancient Monument. The building complex dates from the 19th century and includes office/exhibition buildings, a pump house, five pan houses, a smithy and a salt store. Naturally-occurring brine was originally pumped up from a depth of 40m into a brine tank, which fed the evaporating pans within the pan houses by gravity. As the brine evaporated the forming salt crystals were skimmed off into moulds and transported through to the brick hothouse where the blocks were removed from the moulds and left to dry in the hot air from the furnaces. Salt was then shipped out to Manchester or Liverpool and exported worldwide.

The Lion Salt Works finally closed in 1986 but the trust, set up in 1993, hopes that it can be restored to a working industrial museum where brine will once again be evaporated to make white salt crystals.

View of the site from the canal.

Instruments and software

The requirement for survey was to record the entire pan house complex and the separate salt store, providing full internal and external plans, sections, elevations plus a 'fly-through' movie of the external point cloud. The survey is intended not only as a historical record, but also to form the basis for a full repair specification to be prepared. The survey, funded primarily by English Heritage, was carried out as a joint venture by AEDAS (the project coordinators) and survey firm APR Services. The scanning was carried out using a Leica-Geosystems HDS2500 laser scanner and took a total of nine days on site, completed over three visits. An additional day of scanning was required towards the end of the project when the final 'post plot' was carried out. This filled in small gaps in the scan data that were still too difficult to complete by any other method. A Z+F scanner was also trailed for a future project, the data eventually being used to complete the interior of one of the barns.

Why was scanning selected?

The project was originally specified for a photogram-metric survey, but a proposal to use laser scanning to carry out the majority of the survey was accepted by the Trust and English Heritage as a suitable way to record such a series of structures, which have virtually no straight lines.

The interior of a salt barn.

What problems were encountered?

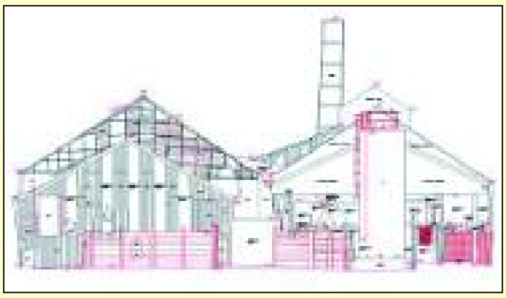
A point density of 10mm on the inside and 10–15mm on the outside of the buildings provided sufficient coverage to draw the individual timbers required. However, this generated a vast amount of data (several gigabytes) which, for ease of handling, was divided up into the internal point clouds for each pan house and a single point cloud for the entire exterior. Scanning was not always easy to complete, as in some areas buildings had collapsed.

It was necessary to use cloud-to-cloud registration to register a few of the scans for areas that were either unsafe or inaccessible to place targets. This software process joins overlapping scans together by comparing and aligning the same geometry within the overlap. This registration process was carried out while on site to ensure coverage, and that sufficient control had been observed.

Interior of salt barn.

What were the final 'deliverables'?

More than 40 elevations, plans and sections were produced using either Cloudworx for AutoCAD or APR Services' Pointools software. Both programs enable the user to view and manipulate the point cloud to produce either 2D or 3D drawings. In order to create the floor plan, a datum height was chosen for each barn. A horizontal section was cut through the point cloud to create a plan at that height. A grid of levels over each floor was extracted from the point cloud along with all beams and main roof timbers.



Elevation to pan houses.

Internal and external elevations were drawn by isolating the individual wall being drawn from the main point cloud and tracing the detail, cutting sections through the cloud where necessary to verify the structure being drawn. Although this is not a fast process, it is probably the quickest method presently available to convert point cloud data to 2D vector drawings.

CASE STUDY 12

Scanning at the edge: assessing the threat of coastal recession at Whitby Abbey, North Yorkshire

type: Airborne Laser Scanning, terrestrial laser scanning (time of flight)
keywords: geohazards, monitoring, management plans

Introduction

Founded in 657 AD, Whitby Abbey occupies a prominent headland site, overlooking the historic town of Whitby. The present remains date back to the 11th Century and are situated alongside associated buildings of historical and religious importance, including St Mary's Church (established in the 12th Century). The site is cared for by English Heritage, and an engaging visitor centre helps to draw large numbers of tourists to the site every year.

The site is under threat from coastal recession.

However, part of the reason why this site is so attractive, is also the root of its vulnerability. Highly visible from both land and sea for miles around, the very existence of this ancient religious site is threatened by the ever-encroaching coastline. The headland is characterised by near-vertical cliffs *c* 60m high. While the abbey itself is still some 160m from the cliff edge, parts of the site have started to suffer the effects of cliff erosion. In 2000 a significant cliff collapse occurred, prompting English Heritage's (then) Centre for Archaeology to excavate and document important archaeological deposits near the cliff edge. Although this may have alleviated immediate concerns, coastal erosion is an incessant natural process, and it is important that organisations such as English Heritage can gain an improved understanding of the longer-term threat so that, if necessary, steps can be taken to preserve this valuable heritage.

Instruments and software

Airborne Laser Scanning (ALS) was flown for the headland area in April 2005 and again in August of the same year. This monitoring strategy was designed to examine the capabilities of ALS for detection of change due to coastal erosion.

The ALS was captured by NERC's Airborne Research and Survey Facility (ARSF) using an Optech ALTM 3033 scanner. This instrument has a specified absolute accuracy of ± 150mm, and is capable of delivering first and last pulse return data. The site was flown at an altitude of 1000m, resulting in a swath width of *c* 680m. This produced data at a resolution of approximately one point per square metre, and the headland area and inter-tidal zone were comfortably captured in three overlapping flight-lines.

Data was collected at one point per metre square.

The raw laser ranges were processed by the ARSF to produce xyz point files each containing several million points. Further processing of this data will be performed using TerraSolid's *TerraScan* and *TerraModeler* software.

Why was scanning selected?

ALS enables continuous coverage over large areas, and is an excellent tool for the rapid acquisition of digital elevation data. It does not suffer from some of the problems associated with photogrammetry, such as the lack of detail in shadow areas, or correlation problems due to poor image texture in areas such as beaches and foreshores. In addition, although ALS is restricted to predominantly dry conditions (to prevent laser returns from raindrops), it is much less weather reliant than image-dependant techniques such as aerial photography. With on-board positioning and attitude sensors for geo-referencing, ALS does not generally require much ground effort in terms of control points, other than one or more GPS base stations (in this case data from the Ordnance Survey's Active Reference Station network was provided).

What problems were encountered?

Problems associated with ALS surveys are often connected to poor reconnaissance and preparation. The number and spacing of flight lines, flying height and desired spatial resolution of the data are all essential considerations that had to be balanced. Gaps between adjacent flight lines can be a problem if the correct overlaps are not applied. Satellite visibility is another concern, and appropriate GPS mission planning is essential.

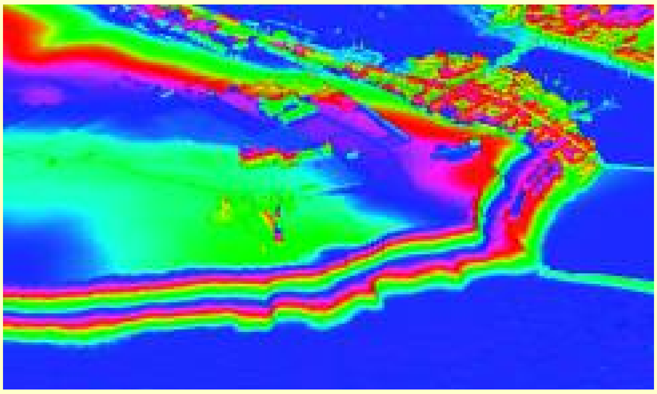
Although the aerial dataset is capable of delivering comprehensive, continuous coverage at a fairy high resolution, it tends to suffer from occlusion problems in areas of steep slopes and overhangs, such as those found on the lower half of the cliffs at Whitby. In spring 2006 terrestrial laser scanning will be used to fill in such data gaps, and provide high resolution modelling of the complex cliff surface.

The April 2005 ALS survey comprised 4.5 million points. This data volume presents significant challenges, not only to data processing, but perhaps more importantly to data storage and archiving.

What were the final 'deliverables'?

Digital Terrain Models (DTM) will be produced by filtering out vegetation, buildings and other artefacts. The DTMs can then be used for comparison and analysis of multi-temporal datasets in order to detect areas of change, which may be a result of coastal recession.

The data sets will be fused together to allow comparisons between the different temporal datasets. This will allow the production of maps highlighting the magnitude and location of changes to the terrain over time. Analysis of this information alongside historical records, such as maps and aerial photographs should enable assessment of the rate of cliff recession at Whitby Abbey Headland. This should prove useful to English Heritage in planning of future preservation works for the site. Work will continue on this project over the coming year, with final results expected in late 2006.



Digital terrain models will be produced.

CASE STUDY 13

Automatic digital reconstruction of a roof truss: laser scanning and automatic extraction of a roof truss in the St. Petri Cathedral Bautzen, Germany

type: time of flight scanning, Development of point-cloud algorithms
keywords: terrestrial laser scanning, roof trusses, automatic extraction, structural analysis

Introduction

Under the high saddle roof of the St. Petri cathedral a truss is located which consists of five floors. Terrestrial laser scanning was used to record the geometry of the bottom floor, which had dimensions of 60m x 31m x 5m.

St. Petri Cathedral, Bautzen, Germany.

The survey aimed to collect data for an automatic digital reconstruction and structural analysis of the truss itself. Although the point cloud contains a huge amount of geometrical information, many users prefer a 2D representation for interpretation. Therefore, the survey also aimed to derive a general 2D plan from the point cloud. Algorithms were developed for an automatic analysis of the scanner data.

Instruments and software

A Riegl LMS-Z420i laser scanner was used for the project. The scanning process is controlled by a notebook and Riegl's RiSCAN PRO software. This panoramic laser scanner has a field of view of up to 80° x 360°. The range finder, based on the principle of pulsed time-of-flight, is able to record distances between 2m to 800m with an average accuracy of ± 7.5mm.

Terrestrial Laser-scanner Riegl Z420i.

Scanning configuration

Because of numerous beams located inside the truss there are many occlusions. The resulting scan shadows were reduced by increasing the number of scanning positions. The selected configuration was a network of 12 scans. At each of the 12 positions a panoramic scan with an angular resolution

360° x 80° intensity image within the roof truss.

of 0.1° was collected. Thus, about three million points were measured at each laser scanner position, which results in 35 million points for the first floor.

Each individual scan had to be transferred into a uniform project co-ordinate system. For this, circular and cylindrical retro reflectors were distributed in the observation area, to serve as tie points. More than three of these tie points were required in adjacent point clouds to obtain a transformation.

Why was scanning selected?

Laser scanning provides the best potential for automation of the recording and analysis of the measurement data. It is also less time-consuming than conventional techniques such as tacheometry or manual measurements.

Furthermore, old buildings often have unstable floors, which result in vibrations that limit the accuracy of the measurements. For example, the truss of the St. Petri Cathedral consists of timber floorboards. Working with a tachymeter was not practicable because of the operator moving around the tripod. Using the laser scanner with wireless data transfer solved this problem.

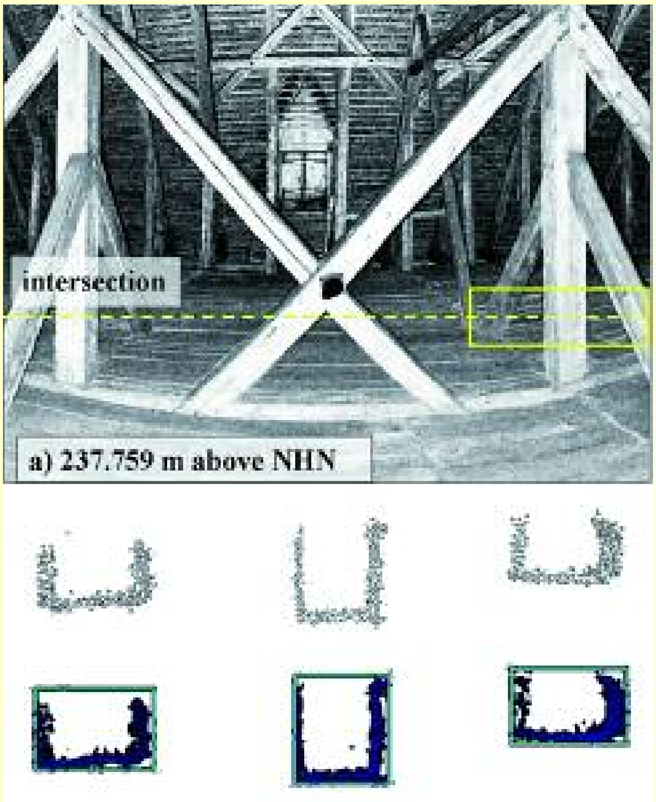
What were the final 'deliverables'?

At first the point cloud was cut and projected onto horizontal 2D layers. An algorithm to segment and model the objects (which are mainly rectangles) was also developed. This was based on the identification of lines using a Hough transformation. The result of this method was a 2D plan of the first floor. Furthermore it is possible to produce maps in different height levels to extend this approach from 2D to 3D.

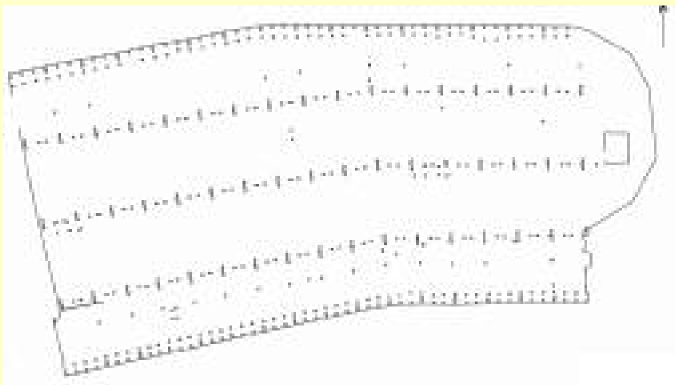
A second method, developed as part of the project, segments and models the 3D point cloud directly using a Hough transformation which identifies planes within the point cloud. The intersection of these planes results in 3D models of the objects.

Approximately 60% of the roof truss could be modelled automatically. As a by-product of these calculations it was possible to extract the topology of the whole truss which can be used together with the geometry for a structural analysis of the truss static.

Further information from: Henze, Wulf-Rheidt, Bienert, Schneider, D: Photogrammetric and geodetic documentation methods at St. Petri Cathedral, Bautzen, Paper presented at CIPA Symposium 2005, Turin (Italy).



Analysis of a intersection plane: a) intensity image; b) 2D point cloud; c) 2D modelling.



Automatically generated map of the floor plan.

CASE STUDY 14

Airborne lidar for ancient landscapes: assessing lidar for mapping large historic landscapes

type: airborne laser scanning
keywords: Witham Valley, landscapes, aerial survey, National Mapping Programme (NMP)k

Introduction

The Witham Valley Research Project has utilised various survey techniques and part of the designated area had already been subject to archaeological interpretation and mapping from aerial photographs. It was decided to compare lidar with the data recorded from the traditional aerial survey methodology employed by Lincolnshire National Mapping Programme (NMP), with particular interest in the usefulness of available archive data flown for non-archaeological purposes.

Instruments and software

Lincolnshire County Council provided 2m resolution lidar data collected with an Optech ALTM 3033 system by the Environment Agency (EA) in March 2001. Based on previous experience with satellite and multi-spectral imagery this was not expected to yield the same level of results as that from the Stonehenge survey. The data was provided in 2km by 2km ASCII gridded files based on the OS grid, which could be used directly with ArcGIS. Because the landscape of the Witham Valley is generally very flat, and a lot of the features had been severely reduced by ploughing over several decades, it was necessary to exaggerate the height ratio in the images up to 20 times to make features evident.

Why was scanning selected?

The EA lidar data was chosen to test the usefulness of standard data not captured for archaeological purposes.

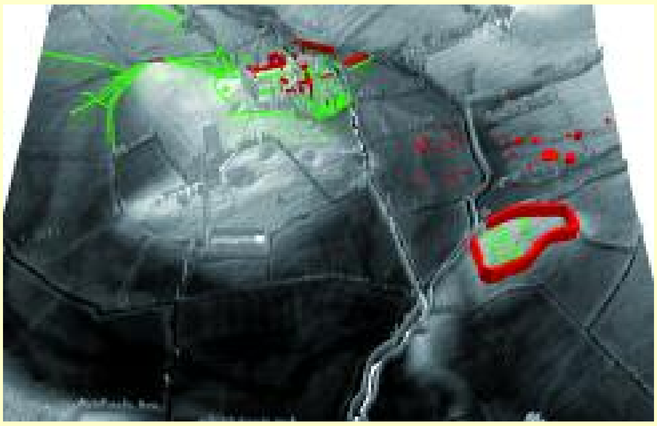
What problems were encountered?

An initial problem was that the interpretation was carried out in the English Heritage York office, where the initial NMP project work had been carried out, while the tools for lidar manipulation were only available in Swindon. This meant that the lidar data was processed in Swindon, after which jpeg images of individual tiles were sent to York.

These images were examined in York and compared with known NMP data and if they were thought to have the potential for additional features that were not immediately visible on the image provided, requests were made to produce new images at a different azimuth or elevation etc. This was not the ideal method for carrying out the survey, but proved workable and produced some useful results.

The second problem was that, as expected, the 2m resolution was insufficient to show any but the largest features, such as field banks.

Southrey shrunken settlement? (LIDAR courtesy of Lincolnshire County Council; source, Environment Agency, March 2001).



Barlings Abbey with NMP data overlaid (LIDAR courtesy of Lincolnshire County Council; source, Environment Agency, March 2001).

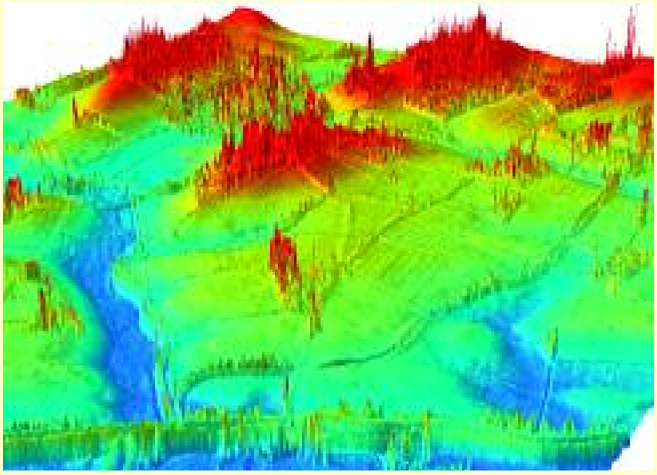
What were the final 'deliverables'?

The key results from this survey were not the DEMs from the lidar, but the interpreted overlays that were compared with previous surveys.

Stixwould

Near Stixwould the lidar data revealed a length of bank more than 750m long, which had previously been seen as a cropmark and recorded as a possible length of Roman road, but was later discounted as a probable field bank or drainage feature. The lidar data combined detail with context to produce another possible interpretation for the feature. The detail showed that this was an extensive broad banked feature at a dramatically different alignment to other field boundaries in the area, and so was clearly not an old field bank or drainage feature. At its eastern end the bank turned sharply to the north and headed straight towards the site of the former Cistercian priory. There are a number of other known causeways providing access to the abbeys and priories in the valley and this may be yet another example.

The context given by the broader DTM shows that this route leads to the main valley bottom, but avoids the lower lying and potentially wet areas.



Stixwould (LIDAR courtesy of Lincolnshire County Council; source, Environment Agency, March 2001).

Bardney environs

A second example can be used as a cautionary tale to emphasise that lidar data simply reflects differences in the height of features on the ground; it draws no distinction between a prehistoric barrow and a modern electricity pylon. It is simply one more source of data and must always be used in conjunction with other available information. Examination of features in the vicinity of Bardney revealed an interesting roughly 'playing card' shaped feature. This was checked against the current OS base map and the 1st Edition and was visible on neither. Indeed the 1st Edition map even seemed to show a field boundary that has since been removed as respecting the line of the feature.

Examination of the site in its landscape context (particularly with the height exaggerated ten times) revealed that it was on a slight ridge with a commanding view over the valley below. The combination of its size and shape and its location gave clear indications that this might be a previously unknown Roman fortlet or signal station. However, further examination of other sources revealed a different story. It was noted when examining the current OS map that the site lay on the edge of a former airfield. Inspection of aerial photographs from during and immediately after WWII showed that this was an area of hard standing leading to a possible hangar or storage building.

Combined lidar 2001 and aerial photo 1946 (LIDAR courtesy of Lincolnshire County Council; source, Environment Agency, March 2001; /RAF 3G/TUD/UK 197 Part VI 5449).

Data for the project was provided by Lincolnshire County Council.

CASE STUDY 15

Forest of Dean: lidar for mapping historic landscapes in woodland

type: airborne laser scanning
keywords: Welshbury, landscapes, aerial survey, National Mapping Programme (NMP)

Lea Bailey Wood, Forest of Dean NMR23322/02 (07-Nov-2003).

Introduction

Since 2000 the Aerial Survey team at English Heritage has been examining lidar data with a view to assessing its suitability. A fresh aspect of lidar and new potential was recognised in 2003 when the possibility of using last pulse data was pointed out in a presentation by Simmons Aerofilms. It was realised that the ability to penetrate tree canopies could be extremely useful in revealing features in areas where traditional aerial survey was unsuitable.

The Forest of Dean had been subject to standard aerial survey techniques as part of the National Mapping Programme (NMP) for Gloucestershire. Using historic aerial photographs taken over a number of years it had been possible to record some features that were visible during periodic phases of felling. But given the nature of the Forest, with a high proportion of land covered by dense woodland, there were large areas where very few archaeological features were recorded.

The Aerial Survey team became involved in a project with the Cambridge University Unit for Landscape Modelling (ULM), Forest Research at the Forestry

Commission and Gloucestershire County Council Archaeology Service to look at the Iron Age hillfort at Welshbury. The site had previously been recorded on the ground by the Royal Commission on the Historical Monuments of England (RCHME), but when the area was covered by the NMP project, very little detail was recoverable because of the density of the vegetation. It was therefore seen as an excellent site on which to test the capabilities of lidar.

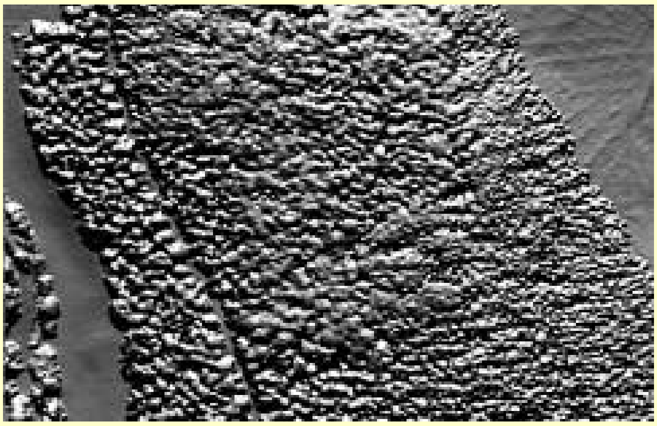
Instruments and software

An airborne lidar survey of the site was carried out in February 2004 using the ULM's Optech ALTM 3033 system. The details of their project are recorded in Devereux *et al* (2005), from which the following technical specifications are also taken. Ground GPS support was provided by a dual frequency, Novatel receiver located at an Ordnance Survey passive recording station. The maximum distance from the base station to the most extreme point on the survey site was 28km whilst the shortest distance was 1.2km.

Two separate surveys of the site were conducted to generate approximate point densities of four per square metre and one per square metre. The size of the laser footprint was set to a nominal 0.8m for the four points per metre survey and 1.25m for the one point per metre survey. By flying the surveys during winter, the deciduous canopy was devoid of leaf cover and the understorey vegetation was at a minimum, thus ensuring maximum laser penetration to the ground surface.

The survey point cloud data were converted to a 0.25m and 1m grid (for the high and low resolutions surveys, respectively) 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 the last one encountered in the point cloud was used. Empty cells were filled by smoothing their neighbours. Images were collected for first pulse, last pulse and intensity (the overall strength of the laser return). Staff at ULM wrote a vegetation-removal algorithm to create a digital elevation model (DEM) of the topography of the site under the forest canopy (Devereux *et al* 2005).

As there is no mathematical expertise within the Aerial Survey team for the writing of algorithms it was felt important to analyse the potential of using just raw last-pulse data to see what information could be gained that was not available from the first pulse. The data was provided to English Heritage in the form of ASCII tables recording the xyz and intensity data for the first and last pulse in a single table. This was separated into tables that could be read into ArcGIS 8.3 where the 3D Analyst module was used to interpolate to raster using Inverse Distance Weighting.



Welshbury Hillfort: lidar first pulse.

The results were very positive in that although they did not remove all traces of vegetation, as was achieved by the algorithms, they did reveal a large amount of previously unseen detail.

Welshbury Hillfort: lidar last pulse.

Why was scanning selected?

The potential of lidar to penetrate the canopy and allow the recording of features that were invisible to standard aerial photographic techniques made it ideal to test in such an environment that is also difficult to survey on the ground.

What problems were encountered?

The Forest of Dean was the first survey area where the Aerial Survey team had direct access to the lidar data and this led to a very steep learning curve in how best to use the data. The large file sizes also created practical difficulties in terms of the processing power of the teams PCs.

On a more technical note, while the processed algorithm left a bare earth DEM the raw last pulse data left a large amount of 'stumps' representing either the actual trunk of the tree or particularly dense areas of foliage that could not be penetrated. This was particularly noticeable in the area of conifer plantation where even the last pulse data was unable to penetrate the canopy owing to the density of foliage. This 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 were the final 'deliverables'?

While the ULM algorithm produced a true DTM the raw last-pulse data produces something between a DTM and DSM as it removes the bulk of the vegetation, but not all of it. This was illuminated from various elevations and azimuths to reveal variations in the surface that might relate to archaeological features. Because the lidar coverage extended beyond the edges of the woodland it was possible to compare the results with those from the conventional NMP survey and confirm the presence of known features.

Devereux, BJ, Amable, GS, Crow, P and Cliff, AD 2005,'The potential of airborne lidar for detection of archaeological features under woodland canopies' Antiquity 79, 648–60

CASE STUDY 16

Generating accessible 3D models: recording UNESCO World Heritage Sites at Ayuthaya and Sukhothai, Thailand

type: ground based laser scanning
keywords: archaeological sites, web dissemination, textured models

Introduction

This was a collaborative project involving the National Electronics and Computer Technology Center (NECTEC), Bangkok, Thailand, and The Department of Spatial Sciences at Curtin University of Technology, Perth, Australia. The aim was to create a realistic and accurate 3D model of this culturally and architecturally significant heritage precinct and to make it accessible over the WWW, thereby providing the archaeological as well as heritage management community, and the general public with the opportunity to examine and visit it remotely. Two sites were recorded: Wat Mahathat in Ayuthaya in March 2003 and Wat Mahathat in Sukhothai in November 2003.

The project tasks were divided between the two groups. The Curtin group were responsible for:

- laser scanning
- control surveys for scan cloud integration
- data management

While the NECTEC group undertook:

- surface modelling
- texture mapping
- web publishing (including the required multimedia functionality)

Instruments and software

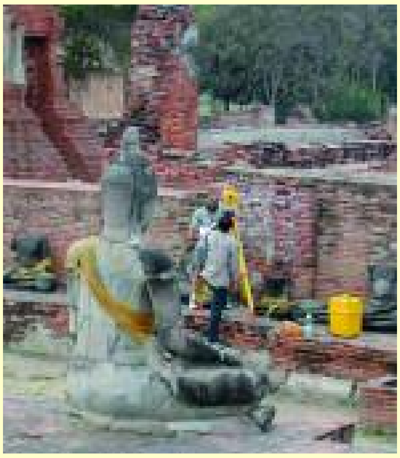
For the scanning, Curtin's Riegl LMS-Z210 was selected since, at the time of project's initiation, it was among the faster instruments offering a nearly-complete horizontal field of view. Rapid and complete data capture was very important since both sites are popular tourist destinations and it was required that our activities would not be a disruption.

The Wat Mahathat precinct within the Sukhothai site.

The I-SiTE software was used for data acquisition, point cloud editing and registration. Geomagic Studio was used for subsequent surface modelling and texture mapping. Software developed by the Curtin University group was used for network adjustment of the surveying data to control point cloud registration.

Why was scanning selected?

Scanning was selected basically for its ability to rapidly capture very dense, accurate 3D datasets.



Large Buddha statue at Wat Mahathat, Ayutthaya.

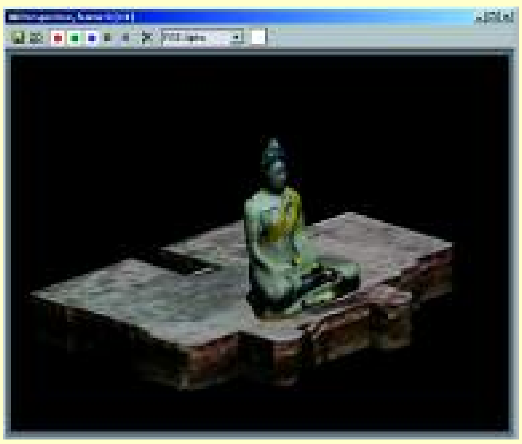
What problems were encountered?

Problems encountered in the field and during processing included:

- providing adequate battery power for the scanner and laptop
- the design of a network to maximise data coverage and minimise data shadows due to occlusions caused by the many structures on site, e.g., chedi, prangs, etc
- planning work around the activities of the tourists on site
- during processing, handling of the merged point cloud of dozen or so scans in the I-SiTE software (which was limited at the time)

What were the final 'deliverables'?

A texture mapped 3D model of each site was the final deliverable.



Texture mapped 3D model of the Buddha statue.

CASE STUDY 17

Earthwork excavation: scanning archaeological excavations

type: terrestrial laser scanning
keywords: long range laser mapping system, time of flight measurement

Introduction

The Discovery Programme's Medieval Rural Settlement Project is undertaking an excavation at an earthwork mound in the village of Tulsk, Co Roscommon, Ireland.

The excavation is revealing at least three distinct phases of activity on site, including the remains of a large masonry tower. Work began in 2005 with the task of excavating through the large amount of rubble that filled the tower's interior. The tower measures some 20m long and 10m wide, and had rounded corners and a battered external wall profile. It seems to have been destroyed by the late 1500s, at which time the mound was reoccupied. The refortification of the mound might be attributed to the presence of Sir Richard Bingham, Queen Elizabeth's Governor in Tulsk in the 1590s.

Instruments and software

In advance of excavation a digital elevation model (DEM) of the site was created by DGPS survey of over 20,000 height points (*c* 1m spacing) referenced to the Irish Grid. GPS processing was undertaken using Trimble Geomatic Office software, with the DEM created using the ESRI's 3D Analyst software.

A DEM of the site in advance of excavation surveyed by DGPS.

A Mensi GS101 laser scanner, controlled by Pointscape 3.1 software hosted on an Itronix pen computer was used to scan the excavation surfaces. Each surface was recorded by between four and six scans, depending on the size and complexity of the surface to be scanned, with the objective being to minimize shadow areas on the scans. Scan resolutions were generally 5mm (at 10m), giving scan times of approx 20 minutes, generating data sets of *c* 200MB. A portable electrical generator was used to provide a constant reliable power source for the digital equipment.

A fixed network of seven control spheres was established around the excavation site, positioned to allow at least four spheres to be seen from any scanner set up. Surrounding this, a series of reflectorless survey targets were used to place all scanning within a pre-known georeferenced framework.

Registration of scans was done in Realworks Survey 5.1, using the automatic registration function. Georeferencing of the registered scans was also done in Realworks. Orthometric views of the RGB point cloud were generated and output as high detail tiff images. The resulting orthometric images were adjusted in Adobe Photoshop to enhance image contrast and brightness. The images were then converted to GeoTIFF images using GeoTiff Examiner software, by applying the pixel scale factors and world X and Y tie points as provided by Realworks as an associated text files. The GeoTiff images were opened in ArcView 9.1 GIS software and displayed with all other relevant site survey data, for example trench grids. Resulting scaled plots from ArcView were printed and laminated to allow field completion and interpretation by the site supervisor to be marked before the excavation proceeded to the next level.

The Mensi GS scanner set up among the masonry remains of the tower.

Why was scanning selected?

The first two seasons of excavation used conventional plan and section drawing to record the excavation, processes that rely on pencil drawing – a time consuming, highly subjective method that has a low level of accuracy and a high level of error. The excavation was revealing large elements of complex stone work, which the graphic survey, using tapes and planning frames, was not satisfactorily recording.

We believed that scanning would be able to provide a much improved quality of record in a shorter time. Additional benefits of the scanning process would be the 3D nature of the data, which would replace the need for conventionally surveyed spot heights, and which would aid visualization and interpretation in the post-excavation phase.

What problems were encountered?

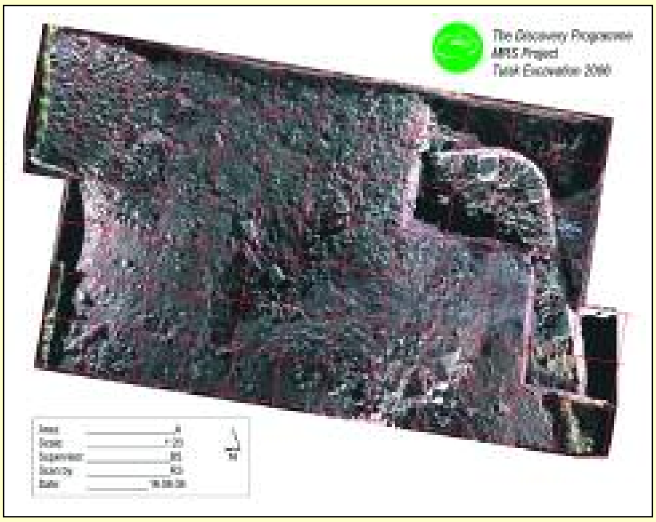
The Mensi scanner has a limited vertical field of view so some of the scan set ups required tilting of the instrument to view down into the trenches. Care was needed to maintain the instruments balance, and that it could still scan the target spheres. It was originally planned to operate through a wireless connection between scanner and control software, but this proved unreliable and was replaced by a fixed 5m network cable. Problems also persisted with network connection cables displaying irregular interruptions between the scanner-to-computer connection. In the field the problem of commonality of control spheres was solved by using a template job, which contained a station set up with all seven spheres observed. In this way any four could be observed from each subsequent station set up.

Weather restrictions were a problem, with the laser scanner not being useable in the rain (due to droplets on the window, and interference of the beam).

What were the final 'deliverables'?

The georeferenced orthometric tiff images of plans and sections are considered our basic deliverables during the field phase of the excavation. These can be produced ready for field verification within 30 minutes of the final scan being completed. This rapid turn around is a vital part of the process as it minimizes the down time of the excavation team, and allows the record to be completed in the field before further excavation takes place. Initial scepticism from the site supervisors was overcome by carrying out a comparison between the laser scanning and conventional hand drawn planning methods on the same surface. The improved speed and quality were immediately obvious, and the excavation team was excited and supportive about the implementation of the laser scanning method.

Beyond the immediate field deliverable the challenge is to merge the point cloud records with the finds positioned by total station survey into a useable GIS 'project'. While seeing the immediate benefit of 'flattening' our data to produce plans and sections, it is important that we generate the added value from the three-dimensional data of our record as well. Assessment of the various point cloud meshing software is currently underway to enable the creation of correct and detailed surfaces.



The final deliverable result.

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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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