Historic England

3D Laser Scanning for Heritage

Advice and Guidance on the Use of Laser Scanning in Archaeology and Architecture

Summary

The first edition of 3D Laser Scanning for Heritage was published in 2007 and originated from the Heritage3D project that in 2006 considered the development of professional guidance for laser scanning in archaeology and architecture. Publication of the second edition in 2011 continued the aims of the original document in providing updated guidance on the use of three-dimensional (3D) laser scanning across the heritage sector. By reflecting on the technological advances made since 2011, such as the speed, resolution, mobility and portability of modern laser scanning systems and their integration with other sensor solutions, the guidance presented in this third edition should assist archaeologists, conservators and other cultural heritage professionals unfamiliar with the approach in making the best possible use of this now highly developed technique.

This document has been prepared by Clive Boardman MA MSc FCInstCES FRSPSoc of Imetria Ltd/University of York and Paul Bryan BSc FRICS.This edition published by Historic England, January 2018. All images in the main text © Historic England unless otherwise stated. Please refer to this document as:

Historic England 2018 *3D Laser Scanning for Heritage: Advice and Guidance on the Use of Laser Scanning in Archaeology and Architecture*. Swindon. Historic England.

HistoricEngland.org.uk/advice/technical-advice/recording-heritage/

Front cover: The Iron Bridge is Britain's best known industrial monument and is situated in Ironbridge Gorge on the River Severn in Shropshire. Built between 1779 and 1781, it is 30m high and the first in the world to use cast iron construction on an industrial scale. In 2012 a laser scan survey of the bridge and immediate surroundings was carried out which would act as both an archive of the structure and as the basis for the creation of a detailed three-dimensional (3D) model for analysis as part of the bridge conservation plan. It is now a major conservation project for English Heritage that will see the different elements of the bridge undergo detailed examination, conservation and repairs to the cracking caused by ground movements.

Front cover: The Iron Bridge
A laser scan survey of The Iron Bridge was undertaken in 2012 that has contributed to the current investigation, repair and conservation of this iconic industrial monument

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Introduction

Document outline and objectives

The guidance presented in this document should provide the necessary information to use laser scanning appropriately and successfully for heritage projects. It is hoped that from the advice given on how the method works and when it should be used, archaeologists, conservators and other cultural heritage professionals unfamiliar with the approach can make the best possible use of this now highly developed technique.

After a brief introduction defining laser scanning and its uses and limitations, section 1 goes on to describe the different laser scanning technologies and systems, both hardware and software, available to users. Section 1 also introduces some of the advances made in equipment and associated software since the previous edition. The methods used to collect, process and manage the laser scan data are presented in section 2. Section 3 then describes how the user can specify a survey (in-house or commissioned) to achieve the intended outcomes. Laser scanning is a very capable and flexible technique but in many cases no single survey tool offers a complete solution, and other methods of three-dimensional (3D) data capture may be required. For this reason complementary or alternative methods are briefly described in section 3.10. Some of the advice provided within sections 2 and 3 can also be applied generally to methods other than laser scanning. This especially applies to data management and the consideration of scale, accuracy and site conditions.

No single document can provide all the relevant information on a subject, and section 4 offers suggestions for further reading, guidance and relevant organisations. Metric survey is a world of technical jargon, acronyms and abbreviations, and these are explained in the glossary. The case studies illustrate a range of interesting applications and describe the varied laser scanning and other techniques used to provide appropriate solutions to fulfil a specific survey brief.

Metric survey

Knowledge of the position, size, shape and identity of the components of a historic building or site is a fundamental part of a project related to the conservation of cultural heritage. The information provides a detailed framework for the assessment of the site's significance, a basis for further conservation analysis and, potentially, by using the survey within the process known as building information modelling (BIM), a structure to which the historical documentation associated with the site can be attached. For example, knowing the size and shape of a mound or barrow located in a historic landscape can help archaeologists identify its significance; a stone by stone computer-aided design (CAD) drawing of a cathedral elevation provides valuable information for an architect to quantify the conservation effort; or, by repeating surveys, a stone carving can be monitored for its rate of erosion, which will assist the conservator in determining the appropriate protection. Traditionally presented as drawings and latterly in two-dimensional (2D) CAD form, the information is increasingly being delivered as 3D data for further analysis, modelling and visualisation.

The choice of survey method can be guided by considering the size of the object, its complexity and its accessibility, but constraints may arise

from the budget and equipment available. In terms of size (scale) and complexity, Figure 1 attempts to differentiate between the available techniques to guide the user towards an appropriate decision. Hand measurements can provide dimensions and relative positions of small objects but they can become uneconomic for larger objects. Total station theodolites (TSTs) are used both for the collection of data and to survey a site control network for all methods. A global navigation satellite system (GNSS) is generally used for geographic information system (GIS) data collection and topographic work.

GNSS is also used to measure control networks, especially when connecting to a national grid.

Photogrammetry and laser scanning are examples of mass data collection techniques (where millions of points can be collected quickly) and are suitable for more complex objects over a variety of scales, including aerial survey. For most projects mass methods still require control networks for overall data unification, and this highlights the fact that there is a strong interdependence between survey techniques.

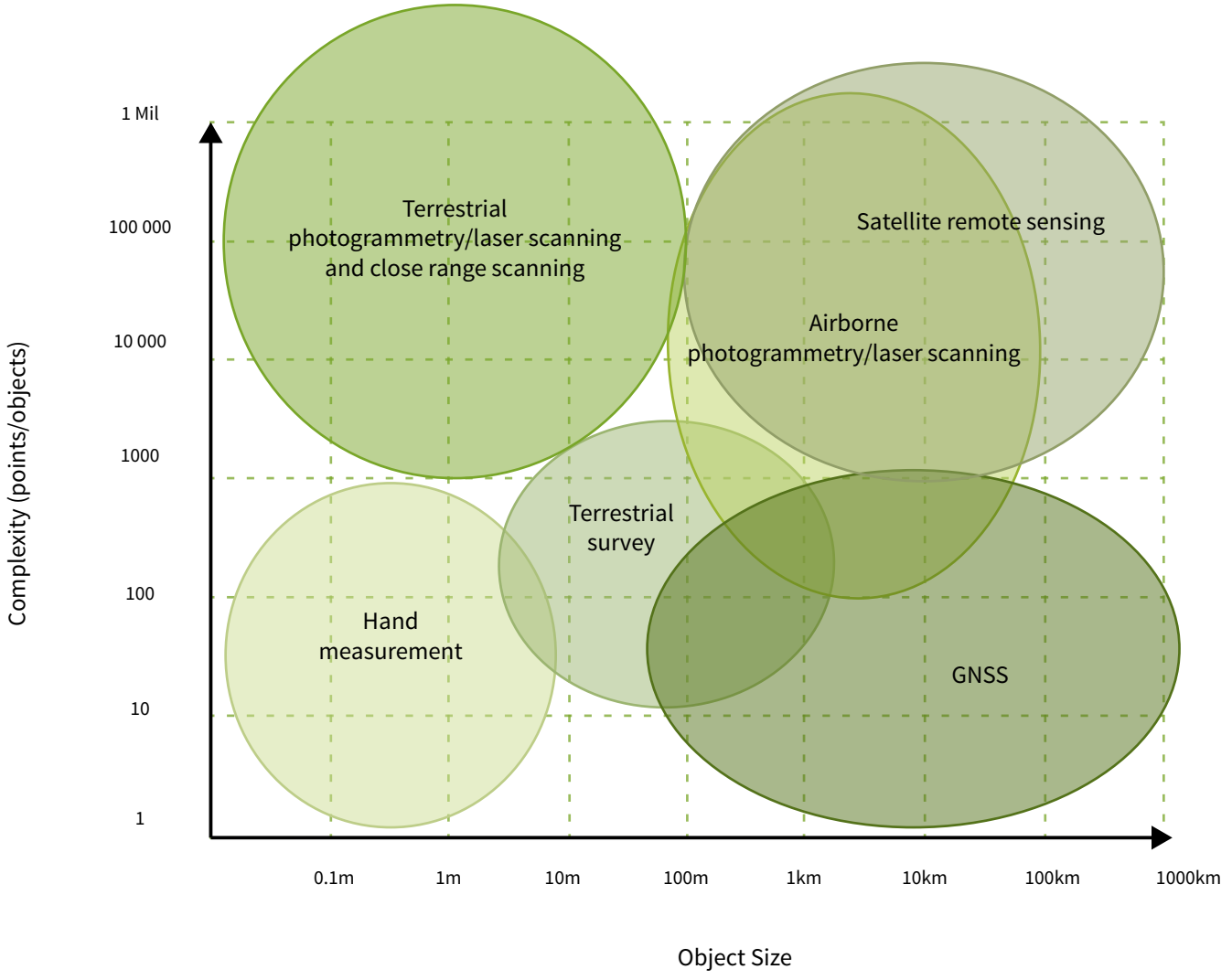
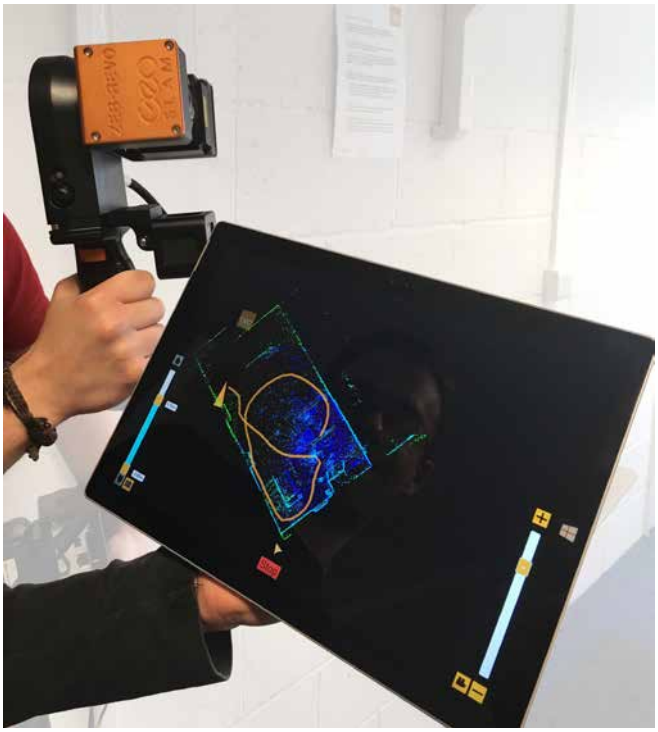


Figure 1
Survey techniques defined by object complexity (points captured) and size, derived from Boehler *et al* (2001)



3D laser scanning

Introduction

Grussenmeyer *et al* (2016, 306) defined laser scanning as 'an active, fast and automatic acquisition technique using laser light for measuring, without any contact and in a dense regular pattern, 3D coordinates of points on surfaces'. Boehler and Marbs (2002) had previously defined a laser scanner as 'any device that collects 3D coordinates of a given region of an object's surface automatically, in a systematic pattern at a high rate and achieving the results in near real time'. There is very little difference between the two statements but the more recent one (Grussenmeyer *et al* 2016) includes the non-contact and active nature of the process. The basic technique and end-product are, therefore, essentially still the same despite the significant progress made in improving the technology. The word active, however, is important because it differentiates laser scanning from passive data collection. Laser scanners emit and receive their own electromagnetic radiation rather than relying on reflected ambient or artificial light as in (passive) photography.

The term laser scanner covers a variety of instruments that operate on differing principles, in different environments and with different levels of precision and accuracy. The data, referred to as a point cloud, can be collected from a tripod, a vehicle or from the air. More recently, handheld and backpack systems have become available that allow data collection while walking around a site. Figures 2, 3, 4 and 5 illustrate examples of each of the types mentioned.

The point cloud is a collection of points converted from range and angular measurements into a common Cartesian (x,y,z) coordinate system that defines the surfaces of the subject in great detail. This is the raw data of the survey, and for each point there is usually information on the intensity of the reflection. The colour of the surface at each point can be added to the coordinate and intensity information by interrogating the imagery from the on-board camera (Figure 6). This is normally done at the processing stage; the colour can also be appended from external photography. More sophisticated instruments, predominantly airborne, can provide information on the range of reflections of a laser pulse and are known as full waveform scanners.

The term lidar (derived from the phrase 'light detection and ranging') is commonly used for aerial, and sometimes terrestrial, survey, but throughout this document it will be reserved for airborne laser scanning. For more information on lidar you can consult *The Light Fantastic* (Crutchley 2010).

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Figure 2 (top)
Leica C10 pulse scanner

Figure 3 (left)
RIEGL VMX-450 mobile mapping system

Figure 4 (centre right)
RIEGL RiCOPTER with VUX-1 UAV lidar

Figure 5 (bottom right)
GeoSLAM ZEB-REVO with optional camera and separate tablet

Figure 6
Section through a unified and colourised point cloud of St Hilda's Church, Hartlepool, County Durham

Uses

Tasks that might be considered potentially suitable for the application of laser scanning include the following:

- A detailed record prior to any intervention at a site to assist in the conservation, refurbishment or analysis process, and as the basis for any redesign work in the form of 3D models (see case studies 1, 5, 6, 9, 11, 12, 13, 14 and 16)
- Working at a variety of scales to uncover previously unnoticed archaeologically significant features, such as small countermarks on coins or rock art (see case studies 2 and 4)
- Structural or condition monitoring, such as observing changes in response to subsidence, erosion, pollution or vandalism (see case study 3)
- A detailed archivable record where a site or part of a site may be lost or changed, such as an archaeological excavation or a site at risk (see case studies 7 and 8)
- Contributing to 3D models, animations and illustrations for presentations in visitor centres, museums and through the media, and therefore improving accessibility, engagement and understanding (see case study 10)
- A digital geometric model of an object from which a replica can be generated for display, or as a replacement in a restoration scheme (see case study 15)
- Aiding the interpretation of archaeological features and their relationship across a landscape, thus contributing to understanding about the development of a site and its significance
- Spatial analysis that is not possible without 3D data, such as line-of-sight investigations or increased understanding through the exaggeration of elevation

It is important to reiterate that laser scanning is unlikely to be used in isolation for these tasks. It is highly recommended that photography is also collected to provide a narrative and visual record of the subject. In addition, on-site drawings, existing mapping and other survey measurements may be consulted or required to aid interpretation and understanding, and to form part of the metadata for the survey.

Limitations

Laser scanning will not provide a solution for 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 unnecessary for the level of deliverable output required. Scanning and, in particular, post-processing of the scan data, can involve a significant effort to achieve the level of results required.

Laser scanners are not as versatile or flexible as cameras with regard to capturing data. Scanners can take over an hour at each position if higher resolutions and qualities are required. This contrasts with the instantaneous camera shot and the ability to use a camera in difficult locations more easily. The latter advantage, however, has been reduced with the advent of handheld mobile scanners. Similar to cameras, laser scanning does require a line-of-sight, ie the process cannot see through objects such as dense vegetation. Scanning systems have minimum and maximum ranges over which they operate and some have problems with reflectance from certain materials, such as marble or gilded surfaces. There are also health and safety factors to consider when using the equipment (see section 2.1.2).

Laser scanning is best suited to the recording of surface information rather than edges. Recording irregular edges precisely can require an extremely high resolution that may not be warranted for the rest of the subject, wasting valuable site and office processing time.

1 Laser Scanning Technology

This section is split into three main sub-sections that cover the scanning hardware and the principles on which each type is based, the systems that combine technologies to provide specific survey solutions, and the field/processing software. There is also a brief sub-section on the specification of computers needed to manage and process the large amounts of data created.

1.1 Scanning hardware

1.1.1 Introduction

Laser scanning equipment has seen considerable advances in the seven years since the publication of the second edition of this document, with increases in the speed of data collection, improvements in the quality of the data by, for example, reducing the noise element, and the development of methods that allow the rapid survey of more difficult areas using handheld and backpack systems. Most laser scanners operate on one of three ranging principles: triangulation, pulse (time-of-flight; ToF) or phase-comparison. Table 1 provides a summary of the different types, including typical system accuracy and operating ranges. The following sections describe each type in further detail.

1.1.2 Triangulation scanners

Laser scanners based on the survey principle of triangulation are available in several different forms:

- Static, sometimes laboratory-based, scanners, used to scan objects placed on a turntable so that all sides are covered
- Scanners attached to articulating arms which provide the positional referencing. They can be either static or taken to the object
- Tripod-mounted scanners, used in the field to scan larger objects and volumes
- Handheld scanners, for close range work
- Handheld and backpack-mounted scanners, for mobile field use over extensive areas

Some of these scanners operate with white light instead of lasers; the light being projected in a structured pattern of stripes or grids. These are, therefore, not strictly laser scanners but they operate on a similar basis. The advantages of structured light include safety and more rapid area coverage. The main disadvantage is that they need to be operated in a controlled environment because ambient light affects the quality of the measurement.

The 3D coordinates are calculated by triangulating the position of a spot or stripe of laser light. The basic premise of a triangulation system is given in Figure 7. In this example the laser is deflected across the subject by a rotating mirror and each reflection is focused onto the sensor by the lens. The location of the point on the sensor, the known separation (D) between the lens and the mirror and the recorded angle of the mirror combined provide a 3D coordinate based on basic trigonometry. As the instrument projects either a dot or a short stripe, the mirror is required to distribute the laser light systematically over the object. An alternative is to use a structured

Scanning System		Usage	Typical Accuracies (mm)	Typical Range (m)
Triangulation	Rotation stage	Small objects taken to scanner. Replica production	0.05	0.1 – 1
	Arm mounted	Small objects. Lab or field. Replica production	0.05	0.1 – 3
	Tripod mounted	Small objects in the field. Replica production	0.1 – 1	0.1 – 2.5
	Close range handheld	Small objects. Lab. Replica production	0.03 – 1	0.2 – 0.3
	Mobile (handheld, backpack)	Awkward locations eg building interiors, caves	0.03 – 30	0.3 – 20
Pulse (TOF)	Terrestrial	Building exteriors/interiors. Drawings, analysis, 3D models	1 – 6	0.5 – 1000
	Mobile (vehicle)	Streetscapes, highways, railways. Drawings, analysis, 3D models	10 – 50	10 – 200
	UAS	Building roofscapes, archaeological sites. Mapping and 3D models	20 – 200	10 - 125
	Aerial	Large site prospecting and mapping	50 – 300	100 – 3500
Phase	Terrestrial	Building exteriors/interiors. Drawing, analysis, 3D models	2 – 10	1 – 300

Table 1
Laser scanning systems and their uses

light scanner (Figure 8), which does not require a rotating mirror. The projected light patterns cover larger areas, which are instantaneously sensed by the two cameras working on the stereo principle. For the illustrated scanner (AICON smartSCAN) the base or distance between the two cameras can be altered according to the size of the object and the precision required. These types of scanner (usually tripod-based) normally operate at ranges up to 2.5m. They can produce data at greater distances but the base length to object distance ratio becomes increasingly smaller and, consequently, the accuracy reduces. They are often used for the detailed survey of archaeological features such as rock art (see case study 4). Structured light scanners also typically perform better in darkened conditions, to increase the contrast between the emitted and any ambient light.

Tripod-based scanners can also be used to scan an object on a turntable. Some of these scanners are laboratory based and, in that case, the object is usually taken to the scanner, restricting their use to smaller movable items. This type of scanning is sometimes offered as a commercial service. There are a number of scanners in this category and they can be quite low cost, such as those produced by DAVID Vision Systems (now part of HP Inc.) (see case study 15).

Some scanners are also mounted on articulating and encoded mechanical arms (Figure 9) that provide the position and orientation of the scanning head in relation to the static object. These are precision instruments and are often used for industrial applications. They can be taken to site but are more often used in a laboratory or workshop. Typically, they operate at a maximum distance of 2–3m with a measurement accuracy up to 0.05mm.

There is an enormous number of handheld scanners on the market. They are mainly aimed at model making at one end of the scale and industrial metrology at the other. There are only a few handheld scanners that are suitable for survey work in terms of their robustness, precision and, most importantly, integration with more rigorous survey software algorithms to produce high-quality cloud registration and geo-referencing. Close-range handheld scanners provide total freedom of movement around a subject but still operate on the basis of triangulation, as they include a light transmitter and a sensor in the same portable and lightweight unit. They use the object itself as a reference between successive scan positions, as long as there is sufficient overlap. In this way, the model builds up in real time and, in some systems, can be seen on an integrated display.

Handheld scanners are sometimes marketed as being complementary to a tripod-based scanner (normally a phase-comparison or pulse scanner) and used to fill in the inaccessible areas. An example is the compatibility between the FARO Focus series of scanners (phase-comparison type;

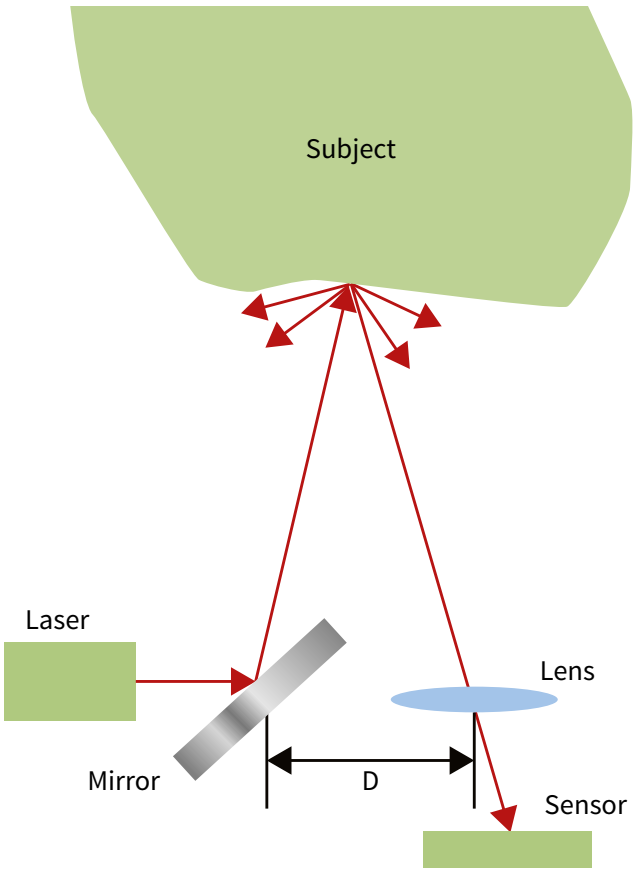


Figure 7 (top right)
A diagram of a mirror-based triangulation system

Figure 8 (centre right)
A structured light scanner: the AICON smartSCAN
© AICON 3D Systems GmbH

Figure 9 (bottom right)
FARO arm scanner
Courtesy of the Interactive Institute Swedish ICT AB

Figure 10 (left)
FARO Freestyle3D X handheld scanner
© FARO Technologies Inc

Figure 11 (right)
DotProduct DPI-8X handheld scanner with integrated Android tablet
© DotProduct LLC

see section 1.1.4) and the FARO Freestyle3D handheld scanner, where both systems use the same suite of FARO SCENE software for data compatibility (Figure 10). The Freestyle3D includes a laser (class 1; see section 2.1.2) projector, two infrared sensor cameras to give stereo detection of the structured light, a colour camera for tracking and realistic photo texturing, and a flash for low light conditions. The system is tethered to a Windows tablet for real-time viewing of both the point cloud and an overlay on the live image of the quality/completeness of the process. The claimed accuracy is 1mm for an 8 cubic metre volume, which is approximately equivalent to a 1.25m stand-off distance at the centre of the volume. An example of a survey-orientated scanner with an integral display is the DotProduct DPI-8X (Figure 11). This uses an Android tablet and an attached off-the-shelf scanner and has similar real-time display of the scanning process. It may not have the precision of the Freestyle3D, for example, claiming an accuracy of 2mm at 1m distance and 10mm at 2m, but it has two advantages in that it sells at a significantly lower cost and all the processing can be conducted on the tablet.

The Matterport Pro 3D camera is a lower cost structured light scanner and camera system that has been aimed, primarily, at the property market. It provides panoramic image and point cloud coverage by rotating at set intervals on its tripod base and is controlled by a smartphone app. The processing and registration are then conducted by the manufacturer on a subscription basis. The advantages are its simplicity of use and the provision of in-view hyperlinks to provide further information. It has a claimed accuracy of only 1% (30mm at 3m distance) so it is not a precise survey tool but can provide good context (immersive and on screen) especially in its 'doll's house' viewing mode.

A recent innovation since the previous edition of this document is the introduction of handheld and backpack-mounted scanners, which can be used to record areas considerably larger than are possible with the scanners outlined above. These will be discussed more fully in section 1.2.4.

1.1.3 Pulse (ToF) scanners

Pulse scanners use what can be considered to be the most straightforward technology: a pulse of laser light is emitted and the time it takes for the return flight is measured. The range is calculated from a simple formula involving the speed of light. However, to achieve this requires a sophisticated timing mechanism and a precise mirror and instrument rotation system to give, in most cases, a 360° view around a vertical axis and between

270° and 300° view about a horizontal axis. This is close to a full sphere of coverage and is the main advantage of the pulse and phase-comparison laser scanners versus the triangulation type. It means that one scan position can cover most or all of a room interior. The fact that the next pulse cannot be emitted until the previous one has been received meant, in the past, that measurement rates were slower than phase-comparison scanners but, with advances in technology, rates of 1MHz (1 million points per second) are now achieved with, for example, the Leica ScanStation P40 (Figure 12).

The energy emitted in a single pulse is greater than the continuous wave of a phase-comparison scanner (see section 1.1.4), which means that the pulse scanner can operate over much longer distances, typically up to 1km but in some cases up to 6km, such as with the RIEGL VZ-6000. The latter is a specialised instrument designed, for example, for geomorphological and glacier-monitoring applications, and is less likely to be used for cultural heritage projects. However, landscape monitoring could be crucial, for example, for ancient monuments sited on unstable ground or prone to flooding. The greater energy in the pulse also means that this type of scanner traditionally operates more effectively than phase scanners in bright daylight.

High accuracies are achieved by pulse scanners, typically 2–6mm even at longer distances, with, generally, less noise than other types. This is sufficient for most cultural heritage applications, and 1mm accuracies can be reached at closer ranges.

An interesting accompanying development with pulse and phase-comparison scanners is the integration of improved cameras, in terms of both resolution and the quality of the image. Typically, a relatively low-resolution camera with a narrow field of view is employed to take a series of photographs over the same area of coverage as the laser scan. The photographs are accurately stitched into a seamless mosaic, which can then be pasted onto the scan data. The mosaicing process is different to conventional panoramas in that it employs the known orientation of each photograph instead of feature detection. It is very important, therefore, that the camera is calibrated precisely by the manufacturer to ensure a perfect registration between the two datasets. In the case of the Leica P40, 260 images are taken to give a 96 megapixel (MP) full dome or hemisphere of coverage.

Part of the improvement in the cameras is their use of high dynamic range (HDR) imaging methods. It is often the case that a full dome of images will have widely varying exposures from, for example, a shadowed side of a building to a bright blue sky or from a dark corner of a room to a ceiling spotlight. The problem is usually overcome by taking multiple images at different exposures (bracketing) for each location and combining these during the stitching and pasting stage in the processing software. Further information can be obtained by consulting the Leica HDR white paper (Walsh 2015).

Figure 12
Leica ScanStation P40 pulse scanner

Figure 13 (left)
RIEGL VZ-1000 pulse scanner with a mounted Nikon DSLR camera
© 3D Laser Mapping Ltd

Figure 14 (centre)
NCTech iSTAR panoramic HDR camera
© NCTech Ltd

Figure 15 (right)
SpheronVR SpheronLite panoramic HDR camera
© SpheronVR AG

The introduction of integrated cameras is to assist in the interpretation of the point cloud. However, even the best scanner camera systems (at, say, 100MP in total) can only achieve medium resolution for the area of a full dome. If the same area is covered with a digital single lens reflex (DSLR) camera (with resolutions up to 50MP for the Canon 5DS, for example) a typical dataset of twenty images will far exceed the resolution of that produced by the on-board cameras. One method, therefore, of improving the image resolution is to use a DSLR mounted on the scanner. Potential registration problems between image and scan are overcome by having a mount coaxial with the vertical axis of the instrument rotation and knowing the vertical offset. This small amount of parallax between views may only become an issue at close range. An example of this type of setup is the RIEGL range of terrestrial scanners, for example the RIEGL VZ-400i and the longer range VZ-1000. The fact that these are not full-dome types (covering only 100° about the horizontal axis) means that they can easily accommodate a camera on top of the scanner (Figure 13). The Trimble TX8 scanner has only a 10MP HDR panorama facility, so Trimble also provides a mount for an external camera. If an integrated camera is not included in the scanner, an alternative is to use a panoramic HDR camera, such as an NCTech iSTAR, which produces a 50MP panorama (Figure 14). SpheronVR also produces panoramic HDR cameras, and its SpheronLite is designed to colourise scans and be compatible with Leica Cyclone processing software (Figure 15). The process involves replacing the scanner on its tripod and ensuring that the camera replicates the position as closely as possible.

Another recent trend for survey-grade pulse scanners is the introduction of a lightweight, lower specification scanner, for example the Leica BLK360, although the FARO Focus range of phase-comparison scanners has always been lighter in weight than the equivalent competition. The BLK360 scanner weighs only 1kg, collects data at 360,000 points per second and includes a 150MP panoramic camera system (Figure 16). The relatively low price of this scanner is aimed

at other end-users as well as professional survey companies. This approach is also exemplified by the bundling of the hardware with Autodesk's low-cost ReCap Pro processing software. The disadvantage in reducing weight, however, is the potential for reduced stability as the scanners contain moving parts. The trend in lightweight scanners is also indicated by the introduction by NCTech (the manufacturers of the iSTAR and iris360 panoramic cameras) of the LASiris VR scanner, which is based on the Velodyne LiDAR Puck VLP16. This scanner has 16 lasers operating through a 30° window but is also rotated around a vertical axis giving full dome cover at 300,000 points per second. It includes an HDR camera system producing a 120MP panoramic image (Figure 17).

1.1.4 Phase-comparison scanners

Phase-comparison (sometimes called continuous wave) scanners, while offering similar accuracies as pulse systems, calculate the range to the target differently. A phase-comparison scanner bases its measurement on the phase differences between the emitted and returning signals rather than directly on the ToF. Phase-comparison systems have traditionally had much higher rates of data capture (greater than a million points per second) as a result of the emission of a continuous wave, but pulse scanners have caught up, at higher end specifications, and the rate increases introduced by competitive manufacturers appear, for now, to have reached a plateau. These high-density point clouds produce very detailed scans for cultural heritage use but can also prove a liability in terms of overkill for less detailed areas of, for example, plaster walling, and in the computer handling of so many points. These issues are addressed in section 2.2.

Technology improvements have meant that class 1 lasers (eg in the Z+F IMAGER® 5010 and Z+F IMAGER® 5016) are generally used now rather than the less safe class 3 type of early developments, for example in the Z+F IMAGER® 5006 first introduced in 2006. For information on laser classes please consult section 2.1.2. In parallel, the range over which phase-comparison scanners can operate has also increased. The limitation was the nature of the technology and the fact that ambiguity over the number of light waves received had to be resolved at the same time as the difference in phase. These and problems with noise at longer ranges have been largely overcome, certainly for the distances required for most cultural heritage projects. They now compare favourably regarding these issues with pulse scanners.

Phase-comparison scanners also include cameras and HDR processing. The Z+F IMAGER® 5016 includes an HDR panorama of 80MP and the new FARO Focus^{S} 350 a panorama of 165MP (Figures 18 and 19).

Figure 16 (top left)
Leica BLK360 pulse scanner
© Leica Geosystems

Figure 17 (top right)
NCTech LASiris VR pulse scanner
© NCTech Ltd

Figure 18 (bottom left)
Z+F IMAGER® 5016 phase-comparison scanner
© Z+F

Figure 19 (bottom right)
FARO Focus^{S} 350 phase-comparison laser scanner
© FARO Technologies Inc

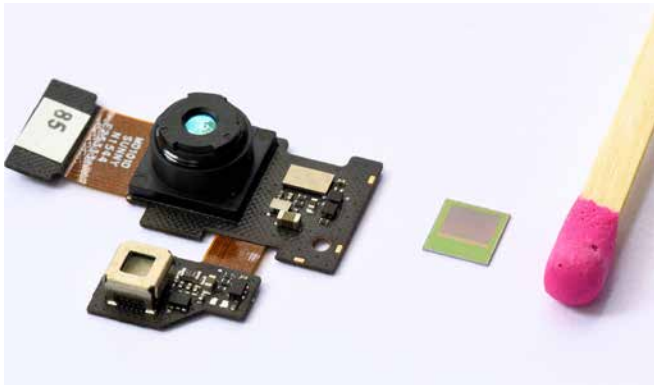


Figure 20 (left)
ASUS ZenFone AR and its array of sensors for the Google Tango augmented-reality system
Courtesy of cnet.com

Figure 21 (centre)
The 3D camera in the Lenovo PHAB2 Pro smartphone with Infineon REAL3™ image sensor chip
© Infineon Technologies AG

Figure 22 (right)
Trimble SX10 combined total station and laser scanner
Courtesy of spatialsource.com

The FARO Focus range of scanners each weighs c 5kg (excluding the tripod), which makes them easy to use and flexible for positioning. They also operate untethered to external power supplies and laptops, which is now the case for most pulse and phase-comparison scanners.

1.1.5 Other scanners

A developing technology is the ToF camera. Instead of a light pulse being received by one sensor, a matrix of sensors can act as an active camera measuring both range and intensity. Matrices are available at resolutions up to 640x480 pixels but their use has been confined mainly to machine vision and industrial applications. They can perform at up 60 frames per second, so a huge amount of data can be collected in a very short time. Because of the instantaneous capture, they are used for moving objects (perhaps in an assembly line) but equally the camera itself can be traversed around a subject similar to a handheld scanner. Google's Tango concept of incorporating depth-sensing tools into mobile phone technology (by Lenovo and ASUS to date) introduces ToF cameras to the consumer for both reality capture and augmented reality viewing (Figures 20 and 21). A miniaturised ToF camera, its infrared projector and a wide-angle camera for tracking are combined to collect 3D point clouds. in real time. Although currently low resolution and the data collection is limited by the available battery and processor power, it will be interesting to see how the technology develops, but there appears to be serious potential for its use in the cultural heritage field.

Another recent development is the integration of a capable laser scanner with a total station. This is the Trimble SX10, which also includes full and part dome (the approximate hemisphere of scan coverage) imaging capabilities (Figure 22). There is some compromise in the design, as the maximum rate of data collection is only 26,600 points per second. However, the use of such an instrument allows the coordination of each scan position and the ability to geo-reference the point clouds directly without the use of control points in the scene. Trimble had introduced scanning into earlier models (Trimble S7 and S9) but the rate was only 15 points per second. Control of the scan data is discussed in more detail in section 2.1.6.

1.2 Scanning systems

1.2.1 Introduction

Although the basic technologies used in the following systems are largely those covered in section 1.1, it is appropriate to consider them separately because they combine equipment essential for their operation other than just the addition of a camera.

1.2.2 Airborne systems

Airborne laser scanners designed for mapping and mounted on conventional fixed- and rotary-wing aircraft use pulse scanners because of the distance to the subject and the strength of signal required at long range. However, because the aircraft is a moving platform it is necessary to integrate the scanner with additional equipment [GNSS and inertial measurement units (IMU)] to determine the location and orientation of the sensor continuously. This information is time stamped onto the data as it is collected, in scan lines perpendicular to the line of flight. These essential measurements are combined by the scanner processing software into a 3D point cloud that represents the topographic surface.

A particular attribute of these lidar systems is their ability to detect multiple echoes from each pulse. For areas of woodland several echoes may be generated by the tree canopy, the shrub layer and the ground itself. This type of system is called a full waveform laser scanner, and the analysis of the data allows filtering to determine the ground level as if it was clear of trees. Line of sight is still required, so if the canopy is dense and no signals can reach the ground then there may be no or very few multiple echoes and the ground remains obscured. However, lidar has revolutionised the discovery of previously unknown or only partly known archaeological sites. An example of the density of data that can be expected is shown by

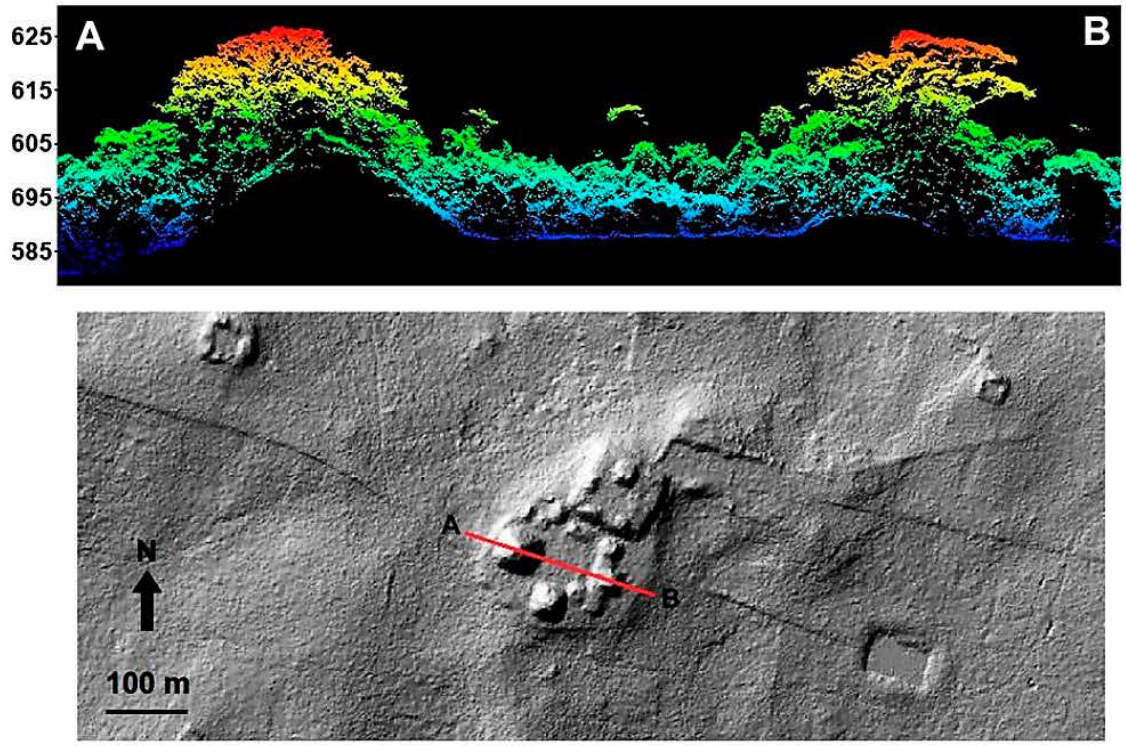


Figure 23
An example of a lidar cross-section revealing Mayan remains at Caracol, Belize
Courtesy of caracol.org

Figure 24 (left)
Leica SPL100 single photon lidar system
© Leica Geosystems

Figure 25 (centre)
Routescene LidarPod scanner for SUA systems
© Routescene

Figure 26 (right)
Velodyne LiDAR Puck LITE laser scanner
© Velodyne LiDAR Inc

the 2013 lidar survey of the Mayan sites around Copan in Honduras (von Schwerin, Richards-Rissetto and Remondino 2016). The mean first return density was 22 points per square metre, dropping to an average of three points per square metre for the ground return and one point per square metre in areas of dense canopy. A good visual example of the ability of lidar to map the ground in forested areas is shown in Figure 23. The cross-section through the canopy shows that up to 30m of tree growth has been penetrated to reveal mounds at part of the Caracol Mayan site in Belize, Central America (Chase *et al* 2011).

Commercially, one recent development is the introduction of the single photon lidar (Leica SPL100), which claims to have the ability to produce an accurate measurement from one photon onto each detector in a 10×10 array (Figure 24). Traditional lidar systems need hundreds of photons to make a confident estimate of the range. This means that data collection with the Leica SPL100 is at a significantly higher rate and density, typically six million points per second and 20 points per square metre. The potential for the improved quality of digital terrain models (DTMs) and their analysis for archaeological use could be significant. The use of a green laser was thought to be problematical when trying to penetrate the tree canopy, producing an excess of noise. However, recent research (Swatantran *et al* 2016) has found that additional processing and calibration can eliminate the noise and improve the accuracy, although at the expense of time and cost. This type of lidar does not have the capability to analyse the full wave or record the intensity of the reflections. Available for some time in the defence industry, the Harris Geiger-mode lidar is a similar development to the single photon lidar but uses a different laser frequency (infrared) and does not have, in its full airborne form, the ability to record multiple returns. Both systems are aimed at high-altitude large-area data collection.

Another recent development is the advent of small unmanned aircraft (SUA) or drones for surveying. This is now common practice but has been conducted mainly using on-board cameras for photogrammetric survey. It has only been very recently that lightweight affordable lidar systems have become available for SUA. A typical system is the Routescene LidarPod based on a Velodyne LiDAR HDL-32E multiple sensor scanner (Figure 25). It can collect 700,000 points per second and has a claimed accuracy (at 100m flying height) of approximately 20mm. The system weighs 2.5kg and, therefore, requires a larger professional SUA with adequate payload. As with the standard airborne systems, on-board GNSS and IMU systems are required for continuous positioning and orientation. The GNSS is also used to navigate the SUA in order to fly in a pre-planned systematic

pattern. For the LidarPod, real-time kinematic GNSS positioning is used to maintain the accuracy required for lidar processing. Velodyne LiDAR also produces one of the lightest lidar sensors available, the Puck LITE, which weighs only 600g and, therefore, could be considered for smaller SUA (Figure 26). One manufacturer that has installed this scanner is SITECO, in their Sky-Scanner SUA lidar product.

RIEGL produces a lightweight lidar and has integrated it into their SUA, the RiCOPTER, which contains their VUX-1UAV scanner, GNSS, IMU, a gyroscopic mount and up to four cameras (Figure 27). It has a 230° field of view, a measurement rate of 350,000 points per second and a claimed accuracy of 10mm. The RiCOPTER can carry a payload of 14kg and has a minimum flight duration of 30min. The VUX-1UAV has full waveform data collection facilities and can, therefore, be considered a miniature equivalent of the large manned aircraft systems already discussed. Their use is more affordable as they are a lot cheaper than other systems and the mobilisation effort for small sites is negligible.

1.2.3 Vehicle-based mobile systems

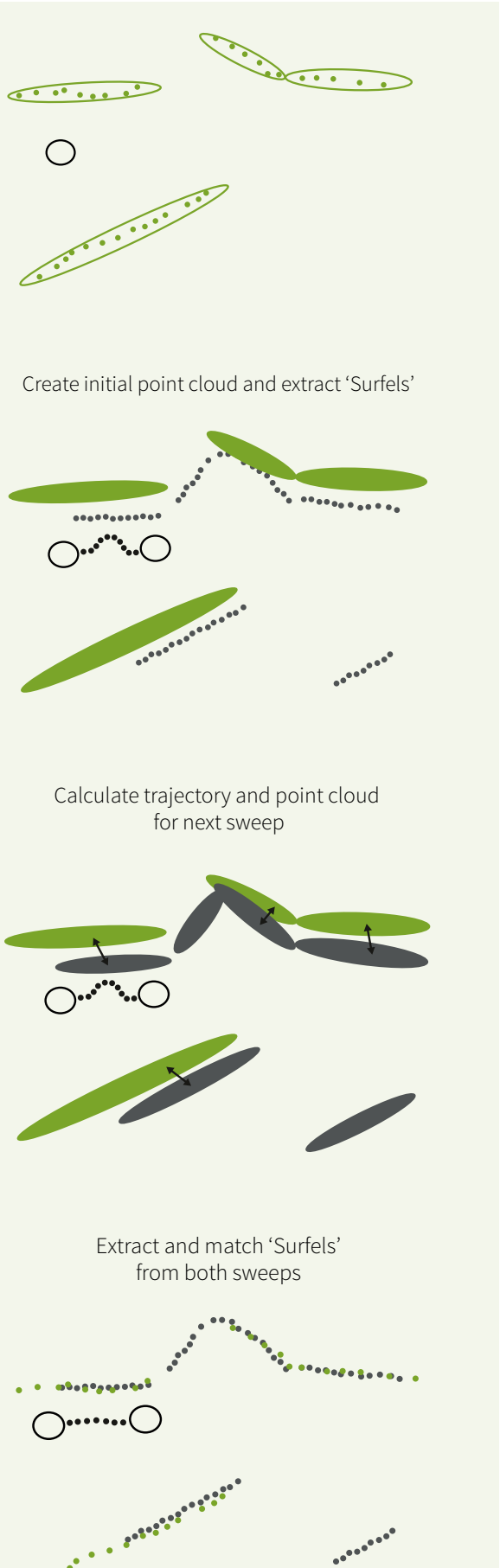
Mobile mapping is now well established and involves mounting one or more laser scanners and cameras on a vehicle in combination with direct positioning and orientation sensors. These systems are generally used for mapping highways or producing city models, although they have also been used in a variety of applications such as the efficient surveying of beach and cliff profiles. As with airborne systems, the movement of the vehicle needs to be recorded continuously for location and orientation of the sensors using one or more GNSS receivers and IMU. An accurate odometer contributes to the dataset and combines with the inertial unit to locate the vehicle when the GNSS signals are weak or lost. This can frequently happen in an urban environment.

In a cultural heritage context, vehicle-based mobile mapping has been used to provide 3D models of historic areas and streetscapes, but in general has seen limited use. It can be used

Figure 27 (top)
RIEGL RiCOPTER with VUX-1UAV scanner and cameras
© RIEGL GmbH

Figure 28 (centre)
Topcon IP-S3 mobile mapping system
© Topcon

Figure 29 (bottom)
Teledyne Optech Maverick mobile mapping system
© Teledyne Optech Inc



to provide an overview or a base plan for more detailed survey of the components of a site, as the accuracies and densities achieved with vehicle-based mobile mapping are not normally sufficient for a more detailed survey. Within historic sites, the size of the vehicle makes access difficult for full occlusion-free coverage and there are potential issues with underground archaeology at sensitive sites.

Vehicle-based systems are produced by most of the larger survey equipment manufacturers and include the Topcon IP-S3 (Figure 28), Leica Pegasus:Two, RIEGL VMX-1HA, Trimble MX2 and Optech Maverick (Figure 29). The latter joins the recent trend towards lightweight easily mountable mobile scanners. 3D Laser Mapping has put together a system based on the RIEGL VMX-1HA (high accuracy version) with a panoramic camera, GNSS and IMU. The 3D Laser Mapping ROBIN has mounts to operate from a SUA, a vehicle or a backpack, which should cover most of the field requirements for collecting laser scan data.

1.2.4 Handheld mobile systems

These instruments have been differentiated from the handheld scanners described in section 1.1.2 as they have been designed as combined systems similar to airborne lidar and vehicle-based mobile mapping equipment. They are a recent inception and have the potential, as they develop, to make a significant change to the way laser scan data is collected, especially in the interior of buildings. For the GeoSLAM ZEB-REVO in particular, the main difference is that the constraint of the tripod and the relatively heavy scanner are discarded in favour of a lightweight (600g) slowly rotating handheld scanner. However, unlike the larger mobile systems, only an IMU is added. As the ZEB-REVO is designed mainly for indoor use any GNSS sensor would be superfluous. The point cloud is built up by using the IMU to calculate the trajectory. This acts as a baseline for the

Figure 30 (left)
SLAM algorithm workflow
After GeoSLAM Ltd

first estimate of the matching process between extracted features and planes (surfels) (Reid 2016). The surfels from successive scans are then matched more precisely, and this match improves the trajectory for the next match. This iterative process is continued until the start point is reached, the closing of the loop being an essential part of the field procedure. This technique (a series of algorithms) is called simultaneous localisation and mapping (SLAM) (Reid 2016) (Figure 30). The range indoors for these scanners is up to 30m and outdoors it is 15m. The accuracies are not as high and noise appears to be greater than conventional scanners but this is offset by the speed at which data can be collected over a large area and the flexibility of being able to access awkward places. The intensity of the echo is not recorded and there is no integrated facility for applying colour images. However, a recent optional addition (ZEB-CAM) includes an attached camera to give contextual imagery and assist in the interpretation of the point cloud. The drawback of the ZEB-REVO has been the lack of feedback on coverage, but this has now been addressed with the introduction of a tablet-based datalogger (see Figure 5).

There are other systems on the market that now include SLAM processing. A system quite similar to the ZEB-REVO (with an IMU but no GNSS) is the Kaarta Contour (Figure 31) but this does include an integrated display for instantaneous feedback of the coverage and registration. Other systems that include GNSS are the Leica Pegasus:Backpack and the backpack version of the 3D Laser Mapping ROBIN. The Leica system includes an array of sensors (two Velodyne LiDAR scanners operating at 600,000 points per second, five 4MP cameras for a panoramic view, GNSS and IMU) all in a backpack weighing 13kg, while the operator monitors data in real time on a tablet. An advantage of such a system is that, because there are five cameras providing a panoramic view, the point cloud can be fully textured with the imagery for better interpretation. This is similar to vehicle-based systems.

Returning briefly to dedicated vehicle-based systems, a recent development has been the introduction of the SLAM method in the

Figure 31
Kaarta Contour handheld laser scanner
© Kaarta Inc

VIAMETRIS vMS 3D mobile scanner, which should provide further refinement to positioning accuracy when GNSS signals are not available. The SLAM algorithms will complement the data provided by the IMU. This technique is likely to become more widespread in future developments of both handheld and vehicle-based mobile mapping systems.

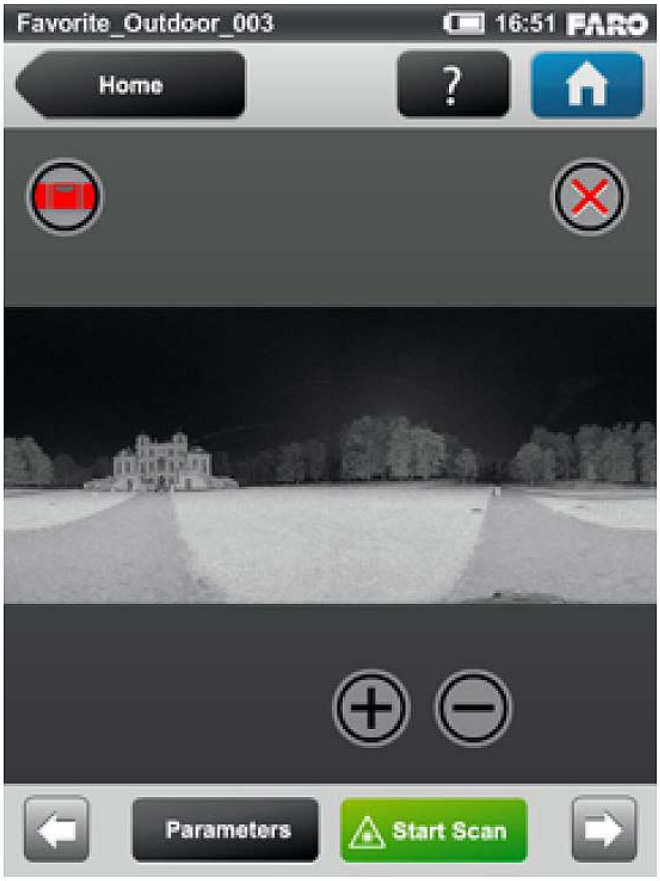
1.3 Scanning software

1.3.1 Introduction

Computer software is an integral part of any scanner system. It not only operates the scanner but also has to store, manage, process, analyse and display efficiently the millions of points generated by the scanning process. The quality and ease of use of the software can have a bearing on the system chosen, so products should be tested fully prior to purchase. This section provides a brief overview and describes some of the important features to consider.

1.3.2 Scanner operation software

The software on board a scanner has to be robust and user friendly, as a surveyor can be working in hostile conditions. The touch-screen operation of, for example, the FARO system, with its large icons and direct feedback of the consequences in time and storage of setting particular parameters provides an ideal design model for field operation. This method has now been adopted by



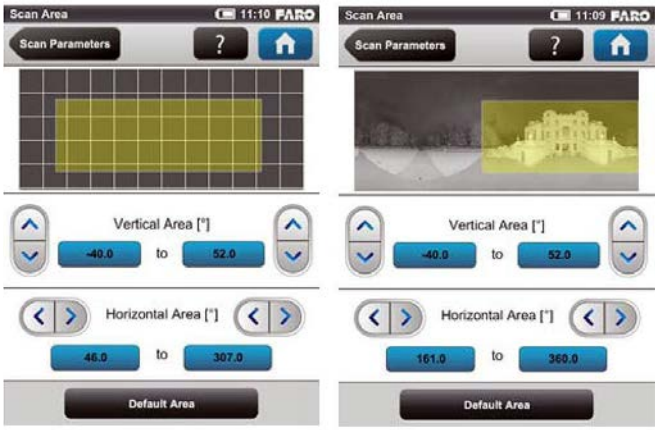


Figure 32 (left)
Grey-scale scan preview on a FARO Focus^{3D}X
© FARO Technologies Inc

Figure 33 (top)
Selecting the area of interest from a preview scan on a FARO Focus^{3D}X
© FARO Technologies Inc

other manufacturers, while FARO has increased the size of the screens on its recent Focus^{S} 350/150 scanners to make them more readable (see Figure 19).

The software should have parameter presets for varying conditions, such as indoors or outdoors, long or short range or for a quick rough scan to determine coverage. This makes operation simpler and avoids having to go through individual parameters for each scan when site time may be limited. However, the software should also make it easy to select, for example, a reduced area of the whole scene to scan at a very high resolution and high quality for, say, a detailed carving. Once the parameters are set the screen should display the file size and the duration of the scan. With experience this information provides an immediate check that the scan will perform the task satisfactorily. Scan times can range from less than 1min to almost 2h. For example, to achieve sub-millimetre resolution at 10m distance with normal sensitivity, a scan on the Leica P40 will take 54min. Such a scenario is rare and would occur only when higher resolutions and quality are required over the full scene. Knowing the duration of the scans will help you plan a day's work, which should include the additional time taken to generate the photography at the end of the scan, usually between 3 and 10min. A file-size information display is also important for assessing the storage medium needs of the project, bearing in mind that average scans can be hundreds of megabytes.

It is essential that the on-board screen displays and magnifies the point cloud immediately after the scan (Figure 32) so that the operator can assess the coverage for potential gaps and see the detail clearly. This helps or confirms the planning for the next location, or provides a base scan in which to define higher resolution part (or window) scans (Figure 33). It also ensures that any control targets in the field of view are visible and scanned with sufficient points. An ability to check the images of the on-board camera, before leaving the current scanning position, is also a useful feature.

1.3.3 Scanner processing software

A description of the software capabilities in conjunction with the data processing will also be covered in section 2.2, but a few important points are raised here. Usually after the cloud-registration phase, the software used for data processing can be a more independent choice. However, there are a number of reasons for choosing from the manufacturers' options, including storage of the data in a proprietary format, close integration and minimising interoperability issues. Examples of laser scan processing software provided by the hardware manufacturers are Leica Cyclone, FARO SCENE, RIEGL RiSCAN PRO, Trimble RealWorks and Topcon ScanMaster.

The software is designed specifically to handle large volumes of point cloud data and will allow the data to be rotated, zoomed and panned in real time, clipped or filtered to avoid overload and the colours to be changed, especially to differentiate the scans. The software should have the facilities to recognise control targets automatically, conduct automatic cloud-to-cloud registration and classify the points by, for example, distance from the scanner, height above ground and intensity of the reflection. Classification of the point cloud assists in the analysis and deconstruction of the data. There should also be more than one method of viewing realistic representations of the subject. The first is by colourising the points using the red, green and blue (RGB) data from the images. Viewing this dataset at more than a point per screen pixel gives a photo-realistic scene. However, when zoomed in the gaps between the points are as evident as if they were not colourised. A more detailed view in close up should also be provided by displaying the actual images as a 360° panorama, assuming the scan covers the same area. Further processing may be available to produce a triangular mesh from the points onto which the images can be accurately pasted, improving interpretation of the data. Some software systems allow direct 3D vectorisation (production of CAD data) from the geo-referenced images.

Mainstream software for CAD, GIS or 3D modelling was not designed to handle the large datasets now routinely generated by laser scanning, and some still cannot do this without additional applications or plug-ins. There are dedicated point cloud processing engines, which hold the data in a parallel database, intelligently access only the data to be displayed, and use levels of detail (LOD) protocols to improve the performance of the mainstream CAD tools. This allows users to maintain their familiar software environment, reducing the amount of new training. Examples of these tools are Leica CloudWorx for MicroStation/AutoCAD/Revit, FARO PointSense for Revit and PointSense Heritage for AutoCAD.

If you are only commissioning a laser scanning survey it is unlikely that you will need to consider what software to use to process the data. You will, however, need to ensure that the final product, generated from the point cloud, can be used for the task intended. This may be at an intermediate stage of the processing, when other users want to pursue additional analysis under their own control. It may be necessary to manipulate the data within a standard desktop CAD or GIS package, or specialist software may be required to enable easier visualisation and analysis. Free point cloud viewers designed for both standard and proprietary formats are available and these can include a few tools (such as coordinate interrogation or simple measurements of distance, area, angles, etc) providing some basic functionality. Examples of such data viewers are Leica TruView Global, Trimble RealWorks, FARO SCENE LT, FARO WebShare Cloud, RIEGL RiSCAN PRO (viewer licence), LFM NetView and Topcon ScanMaster.

The handheld GeoSLAM ZEB-REVO type of scanner registers the point cloud as the data is collected. This is an essential part of the SLAM algorithms on board the scanner. However, the GeoSLAM Desktop software that accompanies the delivery refines the scan registration offline by allowing the operator to set parameters appropriate for the conditions. The manufacturers also include a (web) cloud-processing version called GeoSLAM Cloud as an alternative pay-as-you-go facility.

Backpack systems like the 3D Laser Mapping ROBIN+SLAM and Leica Pegasus:Backpack have in-built data collection and preliminary processing systems. Most of the data processing and extraction is then conducted with existing software packages. The ROBIN is set up for use with Terrasolid laser scan processing and Orbit GT mobile mapping products. The Pegasus:Backpack is recommended for use with the Leica Pegasus:MapFactory for GIS data collection.

Vehicle-based mobile scanning systems tend to have their own dedicated software suites because of the nature of the data collection: point cloud data accompanied by a stream of GNSS, IMU and image information. The suite can consist of applications to collect the data, calculate an accurate trajectory for the vehicle, combine the imagery with the point clouds and allow feature extraction perhaps via a plug-in to a CAD or GIS system. An example of the latter is Leica Pegasus:MapFactory for ArcGIS. It is unusual for a heritage project to require road-based mobile mapping but it is conceivable that a historic streetscape could be mapped very efficiently using this technique. It is even more unlikely that the heritage client will be involved in the data collection or preliminary processing of the information, which would normally be in the hands of an experienced survey company.

For airborne systems the ability to analyse the waveform for different echoes has been available for commercial purposes since 2004, when the RIEGL QMS 560 was introduced (Chauve *et al* 2007). This facility has also been available since 2008 on terrestrial laser scanners. Based on the digital analysis of the complete backscattered signal (using the variation in range and intensity), filtering and classification of the data can be very accurate. This provides information, for example, on the structure of a tree canopy and the understorey as well as the ground. In an archaeological context a precise topographic map of the ground beneath woodland or scrub is very helpful for revealing previously unknown features. The software systems on board the aircraft generally process the data in real time but it is then available to the user, who can apply different parameters to refine and extract additional information. An example of such software is RIEGL's RiANALYZE, which is part of its processing suite RiPROCESS. The Leica LiDAR Survey Studio provides similar functionality for the Leica topographical and bathymetric sensors.

SUA-based lidar systems such as the RIEGL RiCOPTER with the VUX-1 are also capable of full waveform processing, and the data can be processed further using the suites named above. Some systems operate with dedicated software, such as the Routescene LidarPod with its LidarViewer software.

Free and open-source processing software includes CloudCompare and MeshLab. These are both robust systems and are widely used in the survey industry. CloudCompare can register, edit and process raw point clouds, meshes and images. As its name suggests, it can also compare point clouds or meshes to produce difference maps, which is useful for monitoring surface changes over time. MeshLab is aimed at the processing of large meshes and is adept at noise removal, filtering and hole filling to output clean watertight meshes, for example for the creation of 3D-printed models. It can also compare meshes, and both systems maintain a wide range of input and output formats. As shown in the case studies, a commonly used software system is Autodesk ReCap Pro. This provides a user-friendly environment, integration between laser and photographic point clouds and web service computing facilities for mesh creation.

A good data supplier should be able to provide end-users with information on appropriate software to meet their needs (see section 7 for more information).

1.4 Computers

A standard desktop computer may not have the processing capability or even the data-handling ability required for the large datasets generated by laser scanners. However, high-end computers and laptops are available that are very capable and are becoming less expensive. When buying or upgrading a computer, it is essential to refer to the minimum and recommended specification levels for each software package and take into account the amount of data that may be generated. A few other points to consider are outlined below:

- 3D graphics acceleration: having a dedicated 3D graphics card is one of the most important features of a computer, as long as the software is capable of utilising it fully. These cards are usually obtained from third-party suppliers rather than using the generally less powerful graphics cards integrated with the processor. The latter have no or less dedicated memory than those of the third-party suppliers

- Central processing unit (CPU) or processor: the computer's processor is also an important feature of the system, as some software can be processor intensive. It is advisable to consult the software supplier to determine whether its product is processor, graphics card or random access memory (RAM) intensive, in order to make an informed choice on where to concentrate the investment. Generally, the CPU is a less important factor for optimisation of use than having a good graphics card and plenty of RAM

- Memory or RAM: it is usually advisable to invest in as much RAM as possible. The memory chips are normally installed in pairs so, if there is a need to increase the amount of RAM, information on the configuration of the motherboard and its ability to access the additional memory will have to be sought

- Data storage: the hard disc space available for the enormous amounts of data generated is a critical part of the system, although external discs can provide this function and they should also be considered for local backup. Some software uses the hard disc for temporary swap space while processing, especially if the amount of RAM is limited. This can slow down the operation significantly. An alternative is to install a solid-state drive (SSD), which operates at much faster speeds. This may not need a large capacity if it is used just to assist processing and, perhaps, to hold the operating system

- Increasingly, data is being stored in the web cloud; operating system manufacturers and third-party suppliers are offering services that mean the data is available via an internet connection. This is an extremely good way of sharing the data with clients, within an organisation or across the different platforms employed by the end-user. However, these services are not necessarily suitable for the very large volumes produced by laser scanners, except at a price. The data security of these systems also needs to be considered

- Screen or display: the computer screen is another very important part of the system. You may spend much of the day in front of them and for a clear flicker-free display of high-resolution data, higher end-products should be a priority. Many data processors have twin screen systems so that several windows can be open simultaneously. This space is especially useful when displaying a 3D model from several viewpoints

Upgrade paths for existing computers could also be contemplated but, if most of the features need to be renewed, it can be more cost effective to buy a new system. This also avoids compatibility issues.

To use the full capabilities of both computer and software, training should be considered. Dedicated training at the beginning of a project helps avoid bad practice and settings can be optimised for the best performance. Software suppliers, service providers and educational establishments can all provide appropriate training, and some of the organisations listed in section 7 may be able to suggest suitable training partners.

2 Laser Scanning Procedures

2.1 Data collection

2.1.1 Introduction

This section is focused mainly on the use of tripod and handheld/backpack scanners. It is assumed that if airborne or vehicle-based mobile mapping data is required for a project that this will be contracted out to experienced suppliers.

It is important, especially within the context of cultural heritage that records are kept of field operations, including site details, the equipment used, scan settings, control point sketches, scan and photography location sketches, date, conditions, etc. This provides a database of information for users to access for any further analysis that may be required. Information on the metadata to record can be found in the Historic England publication Metric Survey Specifications for Cultural Heritage (Andrews, Bedford and Bryan 2015).

2.1.2 Laser safety

Certain types of laser can be harmful to the eyes. For this reason there is a comprehensive classification system to avoid any potential risk. Lasers are categorised according to the wavelength and the power of the energy emitted. The International Electrotechnical Commission (IEC) defines applicable safety standards, known as IEC 60825 Standards, which have been adopted in Europe and are known as the EN 60825 Standards. Each European country has its own version of these standards; in Britain, the standards document is known as BS EN 60825. The latest version of this, BS EN 60825-1:2014 Safety of Laser Products. Part 1: Equipment Classification and Requirements (BSI 2014) provides information on laser classes and precautions. It outlines eight classes of lasers and users should refer to the IEC Standards document (IEC 2014) to read the full safety information. A summary is provided below:

- Class 1 lasers are safe under all conditions of use, including direct intrabeam viewing. This is the only class of laser for which the term ‘eye-safe’ can be used
- Class 1M lasers are safe for all conditions of use, including direct intrabeam viewing, except when the light is passed through magnifying optics such as microscopes and telescopes
- Class 1C lasers are used for direct application to body tissues and the light is constrained by engineering means. They are not likely to be used in a survey environment
- Class 2 lasers are deemed safe because the natural aversion response (blink reflex of 0.25s and head turn) will limit the exposure. However, dazzle, flash-blindness and after images may occur, especially under low ambient light conditions, which may have safety implications. Repeated, deliberate exposure to the laser beam may not be safe

- Class 2M lasers are also deemed safe because of the natural aversion response, as long as they are not viewed through optical instruments. However, dazzle, flash-blindness and after images may occur, especially under low ambient light conditions, which may have safety implications

- Class 3R lasers exceed the maximum permissible exposure for accidental viewing and can potentially cause eye injuries. The risk of injury is still low unless there is extended exposure. Dazzle, flash-blindness and after images may occur, especially under low ambient light conditions, which may have safety implications

- Class 3B lasers may have sufficient power to cause an eye injury, both from the direct beam and from reflections, and the higher the power the greater the risk of injury. Class 3B lasers are, therefore, considered hazardous to the eye. However, the extent and severity of any eye injury arising from an exposure will depend upon several factors, including the radiant power entering the eye and the duration of the exposure. Class 3B lasers may also produce minor skin injuries

- Class 4 lasers are capable of causing injury to both the eye and skin and will also present a fire hazard if sufficiently high output powers are used. This class of laser is not suited for survey applications

You should always be aware of the class of laser scanning instrument you are using. In particular, you should ensure that the correct classification system is being used (for example the IEC 60825 standard is not adopted in the USA). Particular precautions and procedures are outlined in the IEC standards for laser products that are used in surveying, and these standards should be followed.

2.1.3 Coverage

Planning to ensure that the coverage of the subject is complete or as near complete as practical is an essential prerequisite to any laser scanning survey. A reconnaissance exercise should include decisions on the locations of the scanner to obtain most of the subject in as few positions as possible, followed, normally, by a series of locations that will fill in the gaps because of the presence of, for example, vegetation, vehicles, fencing, etc. The first set of scans will normally include a good distribution of control points but the second set may be matched sufficiently by cloud-to-cloud registration. Other considerations include the time of day, to reduce the presence of people or vehicles, and the position of the sun, to avoid shadows or very bright conditions for the imagery.

The higher levels of building elevations frequently cause coverage problems because of the presence of balconies, recessed windows or just the steepness of the angle (Figure 34). The top image shows the photograph taken from the scanner and the lower image the point cloud viewed more orthogonally. The missing data at the base of the recessed windows is evident. There is often no easy way to cover these laser shadows with scan data, except by using scaffolding platforms or very stable hydraulic platforms. The length of time needed for the scan and the potential vibration or rocking of the support system usually preclude the use of such support systems for very precise work. Extending tripods can be a good, stable way of gaining some extra height (Figure 35). However, precarious or unstable positions sometimes mean that the scanner cannot be levelled easily without adjustment or manipulation of the tripod. If the scanner does not level it is a warning that the position is unsatisfactory, and taking appropriate action at that stage can save valuable scanning time (Figure 36). If an SUA with a scanner on board is available this may provide a solution, but SUA systems are normally used for surveys of larger topographic areas and can be uneconomic as an infill method. From a general survey viewpoint, areas with coverage problems may have to be completed by hand-measurement

or photogrammetric methods. A combination of techniques may be required and this should be borne in mind when planning a survey.

Another important consideration for good coverage is to ensure there is a significant amount of overlap between scans, especially if the survey is heavily reliant on cloud-to-cloud registration. The double or multiple view also has advantages in increasing the potential accuracy, particularly if one view has only a shallow angle to a feature. An orthogonal view provides a better return signal and, potentially, better accuracy than an angled view. Any area of grazing incidence will also suffer from a lower resolution. If only one view is possible this area may need to be scanned separately at a higher resolution to compensate. The variation in angle to the subject will also have an effect on the ground sampling distance (GSD) of the on-board imagery. The GSD equates to the resolution at true scale and this effect becomes important if an image-based product forms part of the deliverables, for example an ortho-image of a building elevation.

Figure 37 provides an example of grazing incidence and a reduction in resolution at distance. The scan lines are more than 1m apart across the ground on the left of the image because of the low angle from a ground-based tripod scan operating at, say, 40m or more. This can be compared with the much higher density closer to the subject area on the right of the image, where the operating distances are 10–15m and multiple scans criss-cross the area.

Coverage considerations for walking handheld and backpack scanners are similar but their flexibility of operation and ability to access tight spots mean that shadow areas are usually less of a problem. The use of the SLAM technique for indoor scanning (and, therefore, without GNSS) requires meticulous planning to ensure that the algorithm can calculate the trajectory accurately. This relies on steady progress, a route that is usually a maximum of 20min to avoid drift and, most critically, a return to the start point. In Figure 38 the red/brown trace in the corridor system to the left clearly shows the out and back traverse to ensure that a completed loop is made.

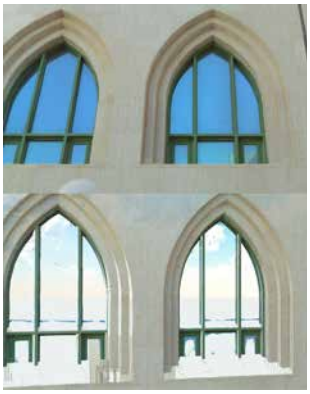


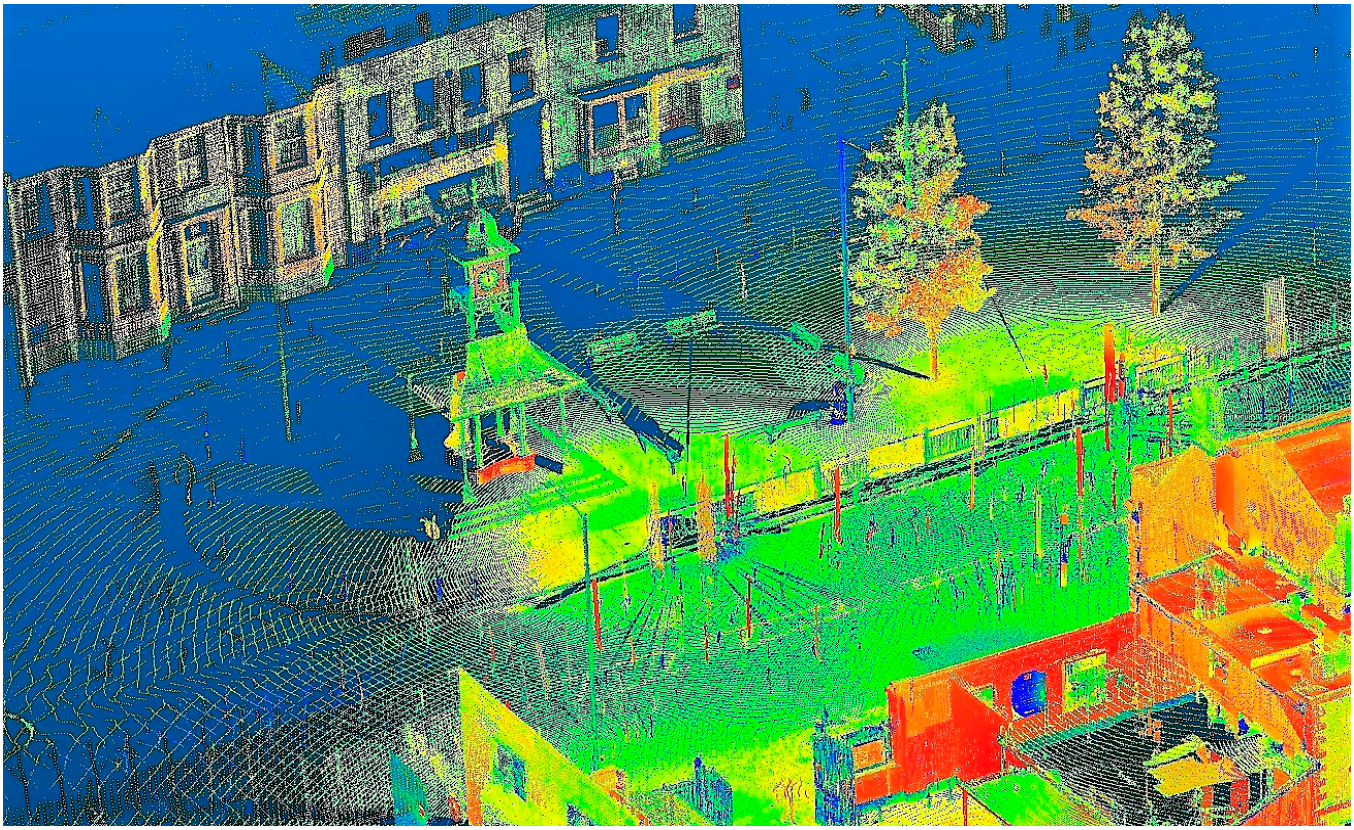
Figure 34 (top left)
Laser shadows at upper levels of buildings
© Clive Boardman

Figure 35 (top right)
A FARO Focus^{3D} X330 on an extending tripod
© IIC Technologies Ltd

Figure 36 (bottom)
Placing a Focus^{3D} X330 on top of a fragile roof
© IIC Technologies Ltd

This is particularly important for long linear areas. These types of scanner can also operate from platforms, scaffolding, crane baskets, etc, because movement of the scanner is not an issue.

For the outdoor backpack scanners (that include both GNSS and IMU systems) there is less need to return to the start point, although accuracy may be improved if this is done. Figure 39 shows a backpack version of the ROBIN in operation.



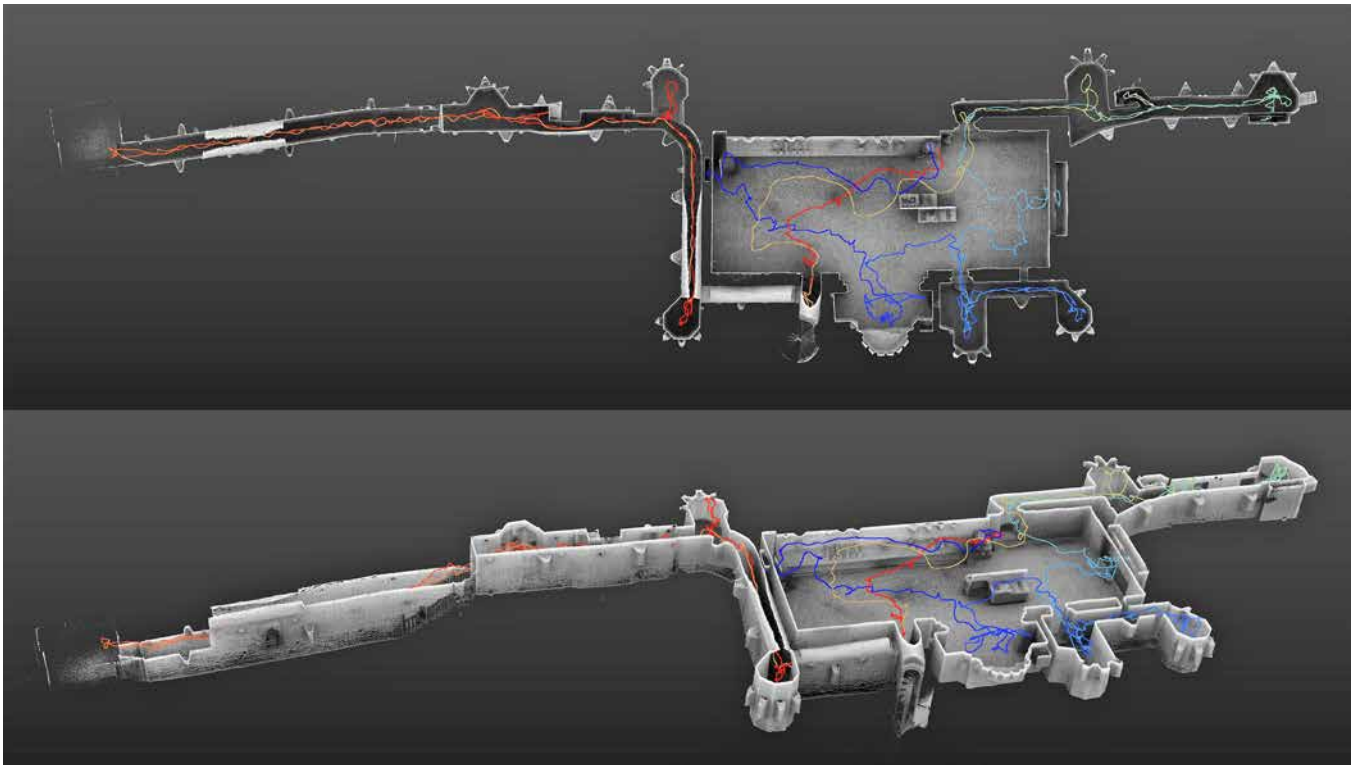


Figure 37 (top)
Reduction in point density as a result of angle and distance
© Stanburys Ltd

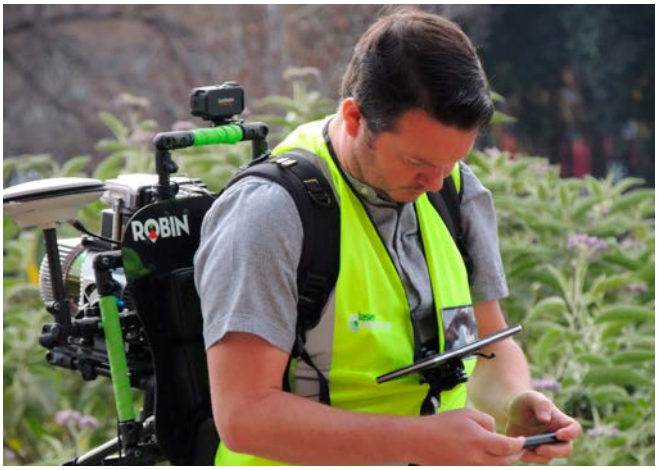
Figure 38 (bottom)
Vertical and oblique views of the ZEB-REVO route and scan data through Thornton Abbey Gatehouse, Lincolnshire
Courtesy of GeoSLAM Ltd and Historic England

It is also worth noting that, for aerial lidar projects, especially in urban areas or of building complexes, coverage can be severely affected by the laser shadows caused by the structures themselves. The planning should ensure that flight routes are designed to minimise the loss of ground coverage.

2.1.4 Resolution and accuracy

Section 2.1.3 touched on considerations of resolution where there are difficulties in coverage, but it is an important topic in itself as it defines the amount of detail that can be seen in the object. There is little point in scanning a modern building at very high resolution if all that is required are the major openings and features. Alternatively, to use a low resolution setting for significant carved detail on a cathedral would miss the intricacy of the work.

The best resolution for any scanner is defined by the smallest angular difference between successive beams. This is measured in two dimensions for static tripod scanners: the rotation of the prism (the horizontal axis) and the rotation of the instrument (the vertical axis). The angular resolution may be slightly different in some scanners. The FARO Focus[s] 3D scanners have an angular resolution of 0.009° in both axes. This is equivalent to a resolution of 1.6mm at 10m from the subject. In comparison, the Leica ScanStation P40 has a maximum resolution of 0.8mm at 10m distance, the RIEGL VZ-400i <0.2mm and the Z+F IMAGER® 5010X <0.1mm. It is extremely rare that these resolutions would be used for full-dome high-quality scans as the scan duration would easily exceed 2h. Very high-resolution settings are more likely to be used for selected area scans where there are high levels of detail at close range or medium detail at greater ranges. At the same time, it is also critical to consider the accuracy of the instrument, which may not approach these resolutions. This is discussed later in this section. Strictly, these figures define the resolution of the instrument and any settings that reduce the number of points stored is sampling (Grussenmeyer *et al* 2016, 308, 308). However, the term resolution is used, almost without exception,



Range	Typical Accuracy	Minimum Accuracy
< 1 m (3.3 ft)	99.8%	99.6%
1 m to 2 m (6.6 ft.)	99.5%	99.2%
2 m to 3.3 m (11 ft.)	99.0%	98.6%
> 3.3 m (11 ft.)	Not Specified	Not Specified

LASER	20m range 190° horizontal FOV 190° vertical FOV Accurate to ± 3cm

Ranging error[4]:	±1mm
Angular accuracy[5]:	19 arcsec for vertical/horizontal angles
3D position accuracy[6]:	10m: 2mm / 25m: 3.5mm

System Accuracy	
Accuracy of single measurement *	
Range accuracy	1.2mm + 10ppm over full range
Angular accuracy	8" horizontal; 8" vertical
3D position accuracy	3mm at 50m; 6mm at 100m
Target acquisition **	2mm standard deviation at 50m
Dual-axis compensator	Liquid sensor with real-time onboard compensation, selectable on/off, resolution 1", dynamic range ±5', accuracy 1.5"

Range noise[5]	<2 mm from 2 m to 120 m on 18–90% reflectivity in Standard modes <1 mm from 2 m to 80 m on 18–90% reflectivity in High Precision mode[2]
Range systematic error[5,6]	<2 mm
Scanning	
Field of view	360° x 317°
Angular accuracy[5]	80 µrad

Figure 39 (top)
ROBIN backpack version
© 3D Laser Mapping Ltd

Figure 40 (bottom)
Accuracy statements from the specifications of a selection of scanners
Courtesy of DotProduct, Kaarta, FARO, Leica Geosystems and Trimble

by manufacturers and users to define the point spacing of the actual scan performed, and that is how the term is used in this document.

It should also be noted that the subject is likely to be at a range of distances from the scanner. The resolution set at a certain range will vary linearly for shorter and greater distances. A resolution of 4mm at 10m will be equivalent to 2mm at 5m and 8mm at 20m. It is important to take this into account when planning the survey, as distant parts of the subject may not conform to the specification. The resolution set defines the point density and the specification may be worded in this form, for example as 10,000 points per square metre. This is equivalent to a resolution of 10mm (100 points along both axes of a 1m square).

The accuracy of the instrument has, or should have, a significant bearing on the resolution that is actually used. If the scanner has an accuracy of 3mm there is little point in setting a resolution better than this. The accuracy statements are generally separated between range and angular accuracies. The former is dependent on the quality of the ToF recording system and the latter on the quality of the engineering of the prism and instrument rotation systems. These factors combine to produce positional accuracies of, generally 2–5mm for tripod-based phase and pulse scanners for normal cultural heritage projects at scan distances of 10–50m. Figure 40 illustrates a selection of statements from manufacturers' specifications indicating the different methods of stating accuracies. This can sometimes make it difficult to differentiate between scanners, and if you are in any doubt you should clarify the specification directly by asking for:

- the range and positional accuracy of the laser dot at the appropriate distances for your projects
- the amount of noise that can be anticipated
- the methods to use to remove the noise
- the scanning and photographic times to achieve your requirements

The divergence of the laser beam at longer ranges also has an effect on the accuracy as it can be more than 10 mm across and will be reflecting back off a surface (or surfaces) that may vary within that footprint. Generally, the handheld and backpack survey scanners have poorer accuracies because of the nature of the data collection. If sub-millimetre accuracies are required for a small area, then fixed or handheld artefact and industrial scanners may be required. The subjects of resolution and accuracy are covered further in section 3.5.

2.1.5 Intensity and colour

The collection of intensity and colour data provides invaluable information for interpretation of the point cloud. Intensity varies according to the reflective properties of the material, the angle of incidence and the distance to the subject, although some scanners can calibrate the intensity so that it is range independent. The informatio n is combined to provide a texture map at between 256 and 65,536 levels of intensity of the surface of the object according to the instrumentation and the settings. This information is collected automatically and simultaneously as part of the range data so that the file storage of each point takes the form x,y,z,I to represent the 3D coordinate and intensity value. This information is useful for interpretation and will be discussed in section 2.2.3.

Although the intensity map provides good tonal differentiation for interpretation, the availability of true colour from a camera provides a realistic representation of the subject. It also provides a record for the user and for archiving purposes that is more easily accessible than the point cloud data. For tripod-based scanners an allowance has to be made for the additional time needed to take the photography immediately after the scanning process, but this is usually only a few minutes. For mobile handheld, backpack, vehicle and airborne scanning systems, the imagery is taken simultaneously. The imagery should be checked constantly and certainly prior to leaving the field to ensure that the exposures are correct. If the camera has an HDR system, this problem is reduced by merging several exposures (bracketing) at each static position.

Each laser point is given a colour based on the RGB values stored for the adjacent pixel so that, on export, the point record becomes x,y,z,I,R,G,B. The benefits of having good-quality imagery to complement the point cloud data for interpretation within the context of cultural heritage cannot be overstated.

2.1.6 Control

An important aspect of the data collection process is determining a control network to which all the other metric field data can be referenced. The specification may not require full georeferencing to the national grid or a site-wide system but it is very likely that it will be needed locally to merge the scans, say, for the interior and exterior of a building. There may be hundreds of scans, and reliance on cloud-to-cloud registration throughout may not produce the most accurate results. It may be impossible to use this method if there is very little overlap between some of the scans.

For accurate registration over a wide area and to georeference the whole area to a site or national grid some, at least, of the control points will normally be coordinated by TST. This will provide control point locations to an accuracy of c 5–10mm, which is normally sufficient in the context of an entire site. This may not seem high but the network will serve to adjust all the scans to a common grid with no or very little impact on the local accuracy within a scan or small set. GNSS methods are also used for control of larger sites but, generally, to a lower accuracy for the height measurements.

The usual procedures for control location apply, requiring a good distribution in and around the subject and avoiding extending data collection outside the network unless there are exceptional circumstances. If this is the case and no subsequent checks can be made, the potential reduction in accuracy should be noted and the client informed. Siting control points to appear on as many scans as possible will strengthen the network. This is easier when using spheres, as they are 3D objects and can be viewed from any angle. A spherical fit is calculated from the many incident scan points. The common use of A4 paper/card targets is a cheaper alternative but they are 2D and are usually fixed to walls. This makes them less likely to appear in as many scans. Figures 41 and 42 show a sphere target and a standard black-and-white 2D chequerboard target, respectively.

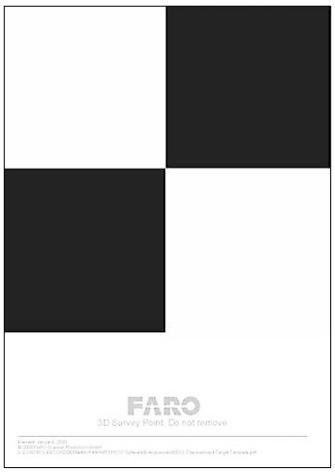


Figure 41 (top)
FARO Focus^{s} 150 scanner and sphere target
© Historic England

Figure 42 (bottom)
A standard 2D A4-sized target
© FARO Technologies Inc

An alternative method to control the scan data is direct georeferencing. If the precise location of each scan station is known and the orientation of the scanner is recorded by referencing similarly to a total station traverse, the point cloud will be georeferenced automatically. Telescope attachments for RIEGL scanners, for example, are available for this method, which could be used

when there is difficulty in placing conventional control points because of access problems. The Leica P40 scanner has survey capabilities and the Trimble SX10 is a combined total station and scanner.

2.2 Data processing

2.2.1 Introduction

Unprocessed point clouds can provide useful information by visualising the project through, for example, static scenes and cross sections. The dataset can, of course, be delivered raw to end users for them to extract information in a CAD or GIS system but, in most circumstances, any further analysis requires the scan data to be processed. Normally, the first major stage is to register the scans to form a merged dataset covering all or most of the subject. Subsequent processing steps to provide deliverable products include:

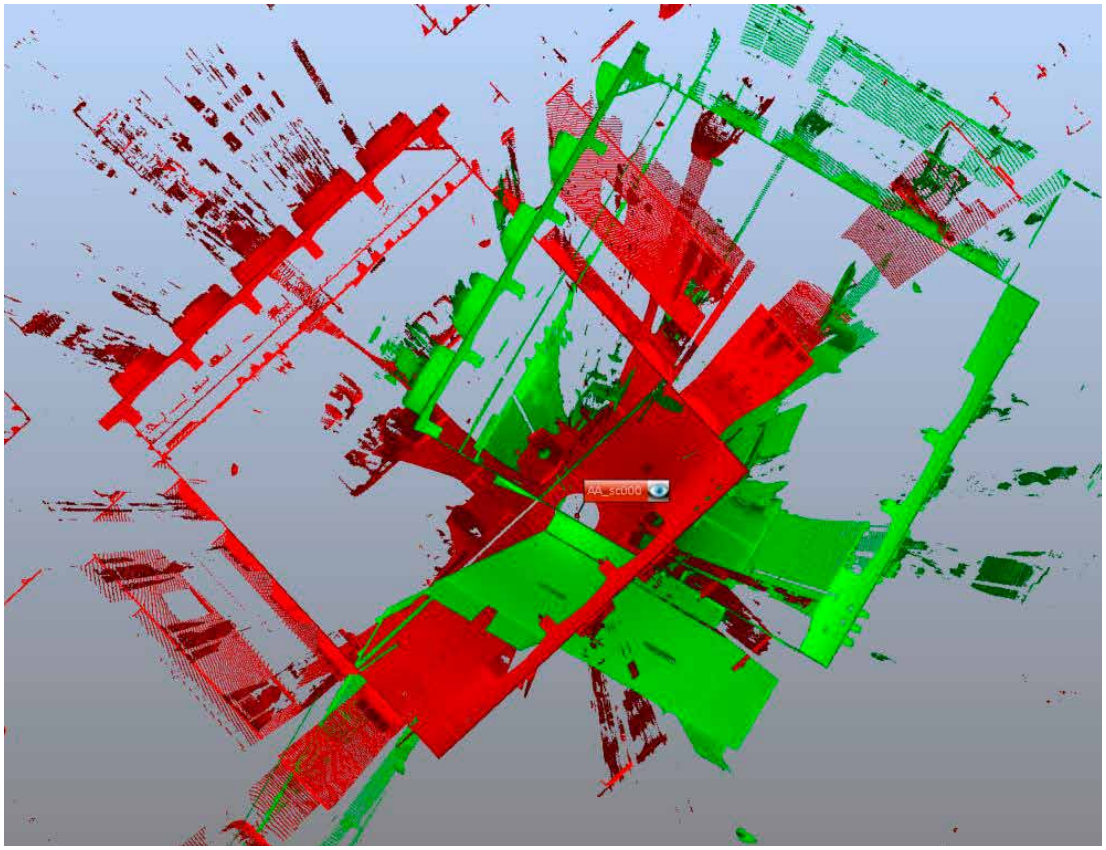
- cleaning
- filtering
- segmentation
- classification
- sectioning
- meshing
- rendering (texturing)
- tracing CAD or BIM detail (vectorisation)
- image-based output
- animation
- visualisation

2.2.2 Data registration and pre-processing

In order to turn scan data into a useful product, the scans must first be registered, generally through the use of additional survey control measurements. Cleaning and filtering the data involves removing extraneous scan data from unwanted features, such as adjacent buildings, people, vegetation, obstructions, data through windows, etc. This exercise reduces the size of the dataset and should make registration more efficient. However, some of this data may prove useful for registration (as long as it is static) in the absence of good overlaps or if there is little control. In this case, the data can be removed after registration. As part of the pre-processing or cleaning up of the data, the noise generated by poor signal return can be filtered out by the processing software. Where a laser dot straddles an edge there can be a confused return, but if the software can handle multiple returns or full waveform analysis then a filter can be set up to accept only the first return to define the edge.

For most objects a number of scans from different locations is required to ensure full coverage. At the time of collection each scan has an arbitrary coordinate system, so the location has to be shifted and the axis orientated into the common coordinate system. This process is known as point cloud alignment or registration. For example, the two datasets in Figure 43 have been imported in the arbitrary coordinate systems in which they were scanned and cannot be used together until they have been registered (Figure 44). In this case the scans were aligned using cloud-to-cloud registration, as there was considerable overlap between the scans at each end of a small courtyard. The quality of the process is reported as having a mean fit of 1.2mm with 86% of the points agreeing to better than 4mm (Figure 45). If the common system is to be orientated to a real-world coordinate system then control points will also be required.

For scanners with active GNSS, each scan will be in approximately the correct position so registration mainly involves orientating the scans and fine tuning the locations. Many scanners also have an integrated compass but care should be taken as metal objects can affect the magnetic field. For airborne lidar, georeferencing can be achieved through the on-board GNSS and IMU systems but, for complete confidence and the ability to check the quality of the fit, control points are still normally used. When using an



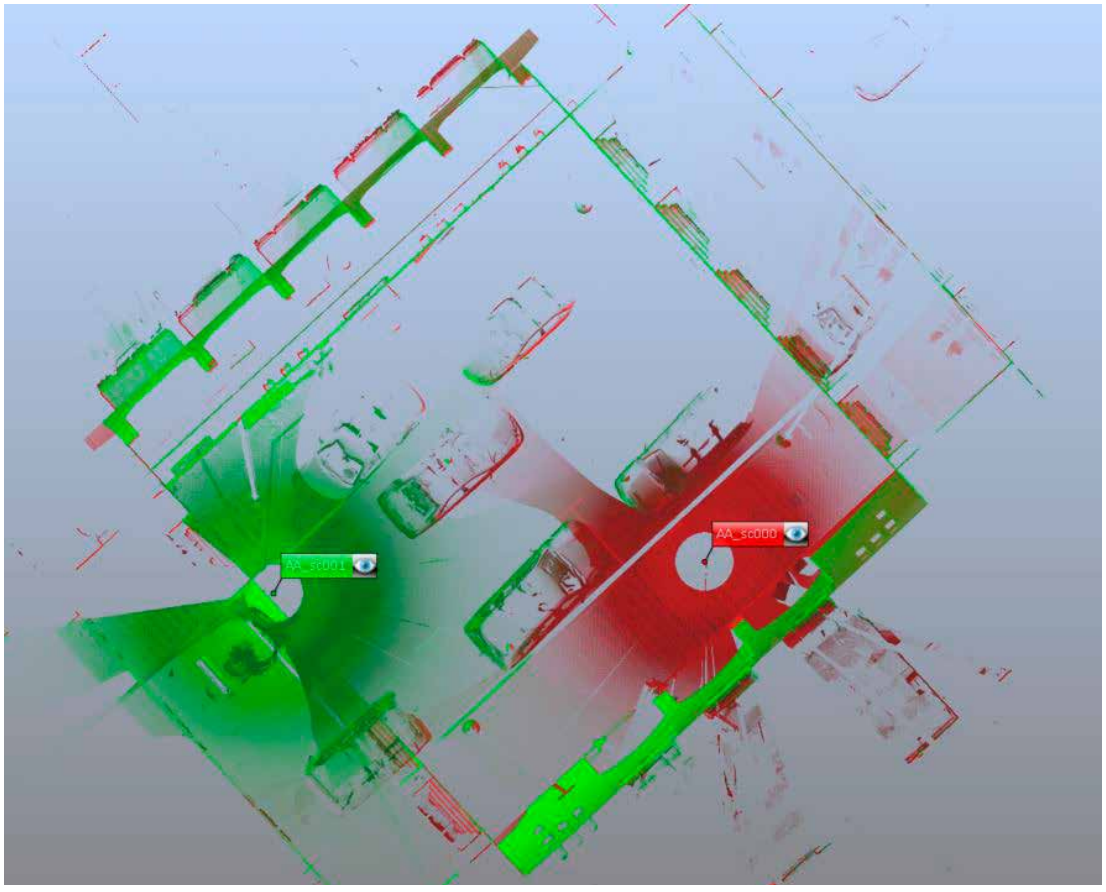


Figure 43 (top)
FARO SCENE unregistered scans
© Clive Boardman

Figure 44 (bottom)
FARO SCENE registered scans
© Clive Boardman

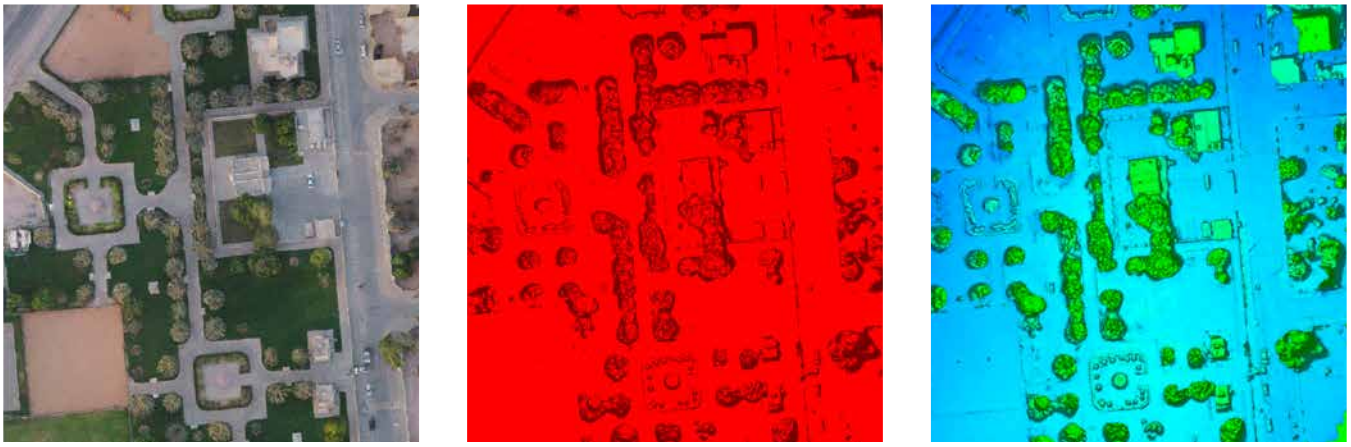


Figure 45 (top)
FARO SCENE ScanFit report
© FARO Technologies Inc

Figure 46 (bottom)
Aerial point cloud displaying (from left to right) RGB colours, intensity and elevation information
© Clive Boardman

arm-mounted triangulation laser scanner, all coordinate measurements are collected in a known system relative to the base of the arm, so additional registration is not required if the scanner remains in one place.

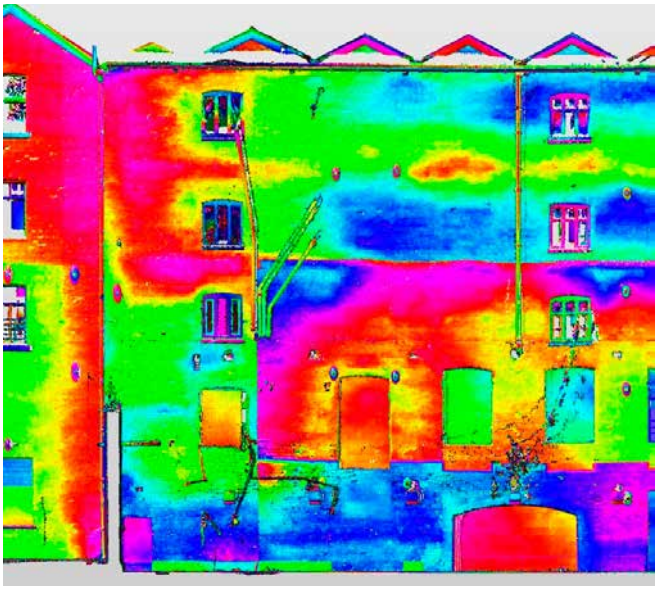
2.2.3 Data segmentation, classification and analysis

The terms segmentation and classification are not always distinguished in the literature. However, '[s]segmentation is the process of grouping point clouds into multiple homogeneous regions with similar properties whereas classification is the step that labels these regions' (Grilli, Menna and Remondino 2017). Classification is, therefore, the identification stage of the process. Basic analysis of the point cloud data can produce classifications according to bands of distance from the scanner or the variation in height from a datum (Figure 46).

In terrestrial scanning, classifying the data into distances from the scanner is a straightforward dissection into ranges that can be set by the user; colouring the bands for ease of viewing. A datum can also be defined above or below which the points can again be dissected into bands. An example of this would be setting a potential flood level to help locate buildings that may be prone to inundation, those that would escape flooding at first-floor level and those that would not be affected. Another example would be using the mean surface of a building elevation as a datum. The bands set at, say, 5mm increments or less would then describe surface deviations and bowing, which may be very helpful in a conservation or structural context. These classifications are equivalent to contours that are derived directly from the point clouds (Figure 47).

A commonly used type of segmentation and classification is categorising features in the landscape according to both their range and configuration. Points that represent buildings, trees and vehicles in lidar datasets display range and shape information that is quite different from the surrounding landscape. The objects rise abruptly above the general datum and have steep sides, and these characteristics separate them from the ground (Figure 48). If these features are removed from the point cloud and the holes are smoothed according to the topography of the immediate surroundings, an estimate of the ground surface is provided that is uninterrupted by artificial and other objects. Parameters can be set within the software to fine tune the classification, and these points are used to generate a DTM.

For airborne systems that include multiple echo or full waveform sensors, the data can be classified according to the first or last echo or any in between. Multiple echoes can occur when scanning woodland, and the echoes can represent the top of the canopy, the understorey and the ground. This data provides information on the structure of the woodland but it also means that if only the last echo for each pulse is retained the point could represents the ground. After appropriate analysis and filtering (see section 1.2.2), this is an extremely effective way of removing the overlying vegetation to reveal features in the landscape that may be of archaeological interest (Figure 49). In Figure 49 the left-hand image shows the first return of the lidar pulse that effectively shows the tops of the trees, similar to a traditional aerial photograph. The right-hand image shows the filtered data processed to remove the vegetation, which reveals the presence of an Iron Age enclosure. The point density is inevitably reduced so the resolution of the ground features may be limited, but nevertheless this method is widely used. Airborne lidar has become a powerful tool in archaeology, allowing users to detect, document and monitor sites (Grussenmeyer *et al* 2016, 357, 357).



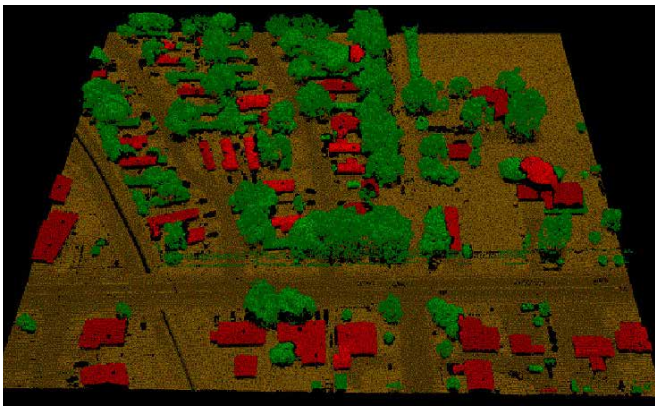


Figure 47 (top)
Deformation map of a building façade

Figure 48 (bottom)
Classification of vegetation and structures by colour

Most survey laser scanners provide simultaneous values that measure the strength of the returning signal (see section 2.1.5). This intensity data can be useful as an additional information source during analysis. As most scanners operate outside the visible spectrum, the intensity map can delineate features that are not observable with the naked eye. Research has also found that analysis of the intensity data can reveal, for example, humidity, old cracks and substrate changes in walls (Lerones *et al* 2016), and help identify forest tree species (Kim, Hinckley and Briggs 2009). Subtle changes in surface or

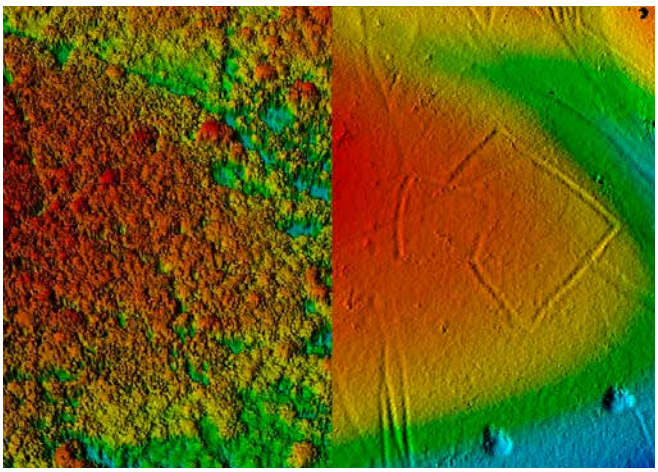


Figure 49 (top)
Lidar imagery demonstrating canopy penetration in open woodland in Savernake Forest, Wiltshire
© Historic England Source: Cambridge University Unit for Landscape Modelling March 2006

Figure 50 (bottom)
Intensity encoding according to amplitude (left) and reflectivity (right). The brightness is almost independent of range
© RIEGL GmbH

material type can also be identified, especially using the greater sensitivity provided by high resolution intensity mapping. Although some scanners do provide a calibration of the intensity values, they normally provide relative variation.

If absolute values are needed for comparison, a user calibration would be required. The RIEGL V-Line range of scanners can process the intensity data according to the amplitude of the return (the standard intensity map with a variation in reflectance based on both the material and range) but also according to a more range-independent reflectance. The intensity for the latter is, therefore, more of a measure of the reflectivity of the surface and may help to improve interpretation further (Figure 50).

2.2.4 Mesh production and modelling

For the production of a true surface model, the point cloud has to be converted into a mesh. This is normally a triangular mesh, with the triangles varying in size to represent the surface as accurately as possible according to the density of points within the point cloud. This mesh is referred to as a triangular irregular network (TIN).

For the modelling of smaller objects such as artefacts and bones, a very detailed mesh can be produced from the high density of points produced by a triangulation scanner (Figure 51). Some highly reflective objects may not produce a complete surface and some editing and hole filling of the model may be required. Parameters can be set within the processing software to fill the holes according to size. In Figure 52 the colours represent each of the five scans taken on a turntable and the final plain textured model has the hole-fill setting activated. This refinement of the model can also be conducted in third-party open-source software such as MeshLab or CloudCompare. For terrestrial or airborne survey scans, the mesh production is usually an early step in a series of processing stages, which includes the production of ground models. Other outputs, such as ortho-images, plans, elevations and sections, will be discussed in section 3.8.

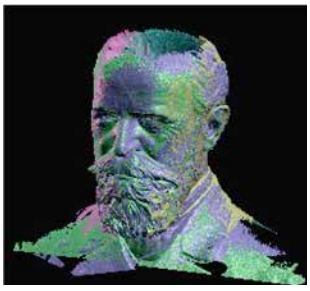
A surface model can be created from a classified dataset (see section 2.2.3). Points that are above ground are removed or ignored to produce a DTM or bare earth model. The surface without these features removed is called a digital surface model (DSM). By employing user-driven semi-automated algorithms, the DTM is used as a reference to classify other points as, for example, vegetation and structure classes, where appropriate. The DTM is usually a TIN so that the ground can be represented accurately and incorporate sudden breaks in slope. However, for use in a GIS, the TIN is sometimes reduced to a regular grid of elevations at, say, 1m or 10m intervals, according to scale.

Another useful technique for analysing a surface is to use artificial raking light to illuminate a scene from directions not possible if relying on sunlight alone. This shading technique is available in most CAD and 3D modelling software. Subtle features may also be identified using vertical exaggeration of the elevation or z coordinate. Slight variations in topography or surface deformation can be combined with artificial lighting to enhance their presence further.

As laser scanning provides 3D data, it lends itself to 3D queries. Line-of-sight analysis allows you to quantify whether one part of the model can be seen from another location, for example to resolve whether a new development will interfere with the view from an ancient monument. This technique is frequently used in landscape analysis.

As meshes can produce large files, there are options to reduce (decimate) the number of triangles. This is generally an intelligent exercise in which the surface is analysed for variations in angle between adjacent triangular planes. Where the angles are low the surface is relatively flat and it may be just as accurately represented by a few triangles. In Figure 53 the tin mesh is reduced from 1.3 million to 50,000 triangles without a significant loss of detail for texturing purposes. The mesh is reducing clockwise from top left to textured model at bottom left. Where the angles are steep, defining edges or sudden breaks in slope, there is less scope for decimation as an unwanted smoothing effect will occur. In other contexts there may be a requirement for smoothing as this could help reduce the effects of noise in the data.

Once the mesh is produced, a plain texture can be added to each triangular face, which will provide a first visualisation of a surface whether it is a topographic DTM, an artefact or a building elevation. This is visually more pleasing and useful than viewing a point cloud as it does not deteriorate or disappear as you zoom into the data. A mesh produces an accurate surface model, provides a deliverable in itself and forms the basis of other products. However, a mesh is not an intelligent model in terms of CAD or BIM data, with their inherent geometric structure and



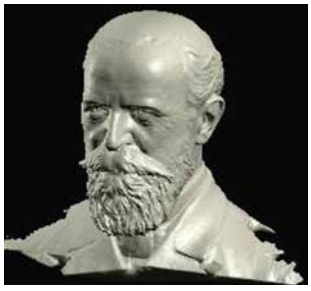


Figure 51 (top)
Textured mesh models of a bone spoon
© York Archaeological Trust

Figure 52 (centre)
Model of a bust using a DAVID Vision Systems structured light scanner
© HP Inc

Figure 53 (bottom)
TIN mesh of a skull
Courtesy of MeshLab at the Visual Computing Laboratory ISTI-CNR

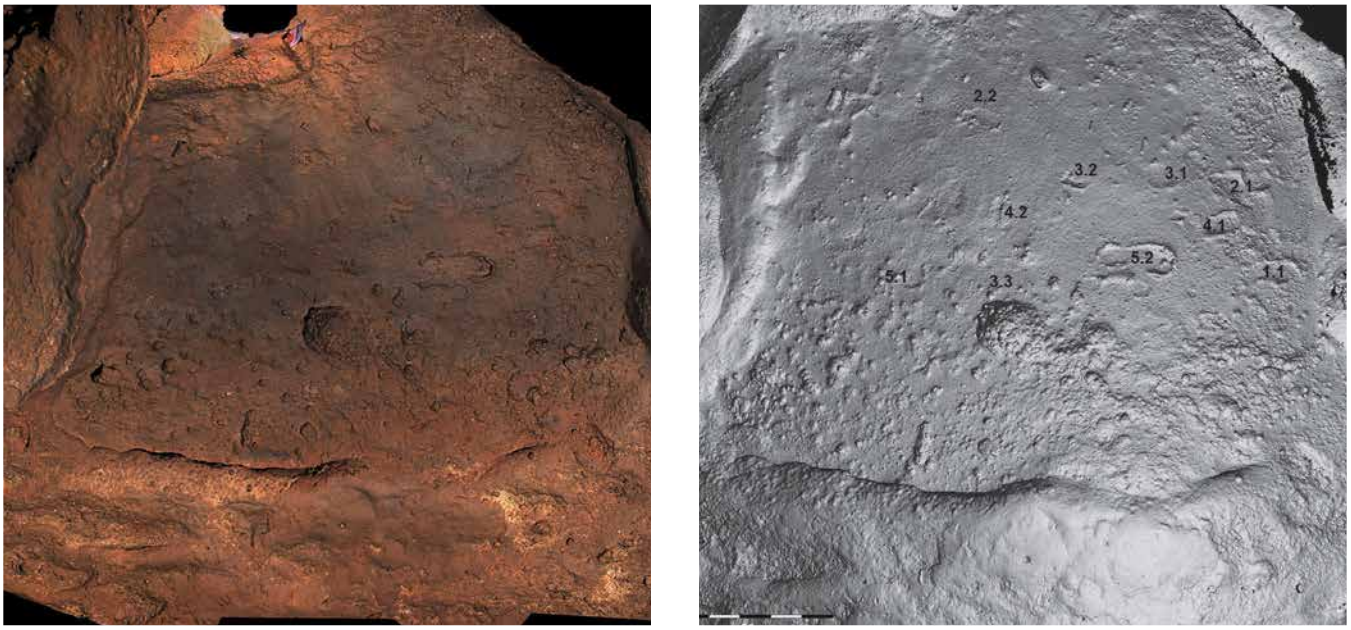


Figure 54
Colour image- and plain-textured models of Pleistocene footprints in Pech-Merle cave, France
Courtesy of the Neanderthal Museum, Mettman, Germany and AICON-Breuckmann

attributes. The production of a mesh may not be required or it may not be the most efficient way of collecting the shapes and dimensions of features. CAD and BIM software allow direct modelling from the point cloud (see section 2.2.6 on vectorisation).

2.2.5 Model texturing and image-based output

Plain textures applied to a mesh can be shaded to accentuate any relief. CAD software suites include libraries of various materials that can be applied to surfaces. These include brickwork, masonry, concrete blocks, marble and timber, but they are not often very realistic and patterns repeat. However, the advantage of using these plain textures or CAD materials for rendering is that it is quick and there is little impact on file size.

For more realistic texturing, photography of the object is applied to the mesh. As well as being aesthetically more pleasing it has the benefit of providing a snapshot of the status of the surface at the time of the survey and can assist with interpretation. Many scanners include a good-quality but relatively low-resolution camera but compensate for this by taking many images that are merged to produce a panoramic photograph of the entire dome. The panorama is automatically registered with the point cloud, and some scanners include an HDR facility to compensate for any large variation in exposure. As the panorama covers the whole area of the scan, it is extremely useful in the interpretation of the point cloud. Access can be given to the panoramic imagery using free viewers available from the scanner manufacturers (see section 2.3.3).

It should be noted that image rendering can detract from the interpretation. A complex texture may mask the topography of the surface. An example is given in Figure 54, where the shaded plain-textured model reveals the footprints more readily than the colour image-textured model.

The resolution of the imagery can be improved by using an external 35mm DSLR or mirrorless camera with resolutions up to 50MP per image. These are not normally used for the whole scan dome but to cover, for example, a building elevation. Unless the imagery is taken precisely in the same position as the scan, there will be

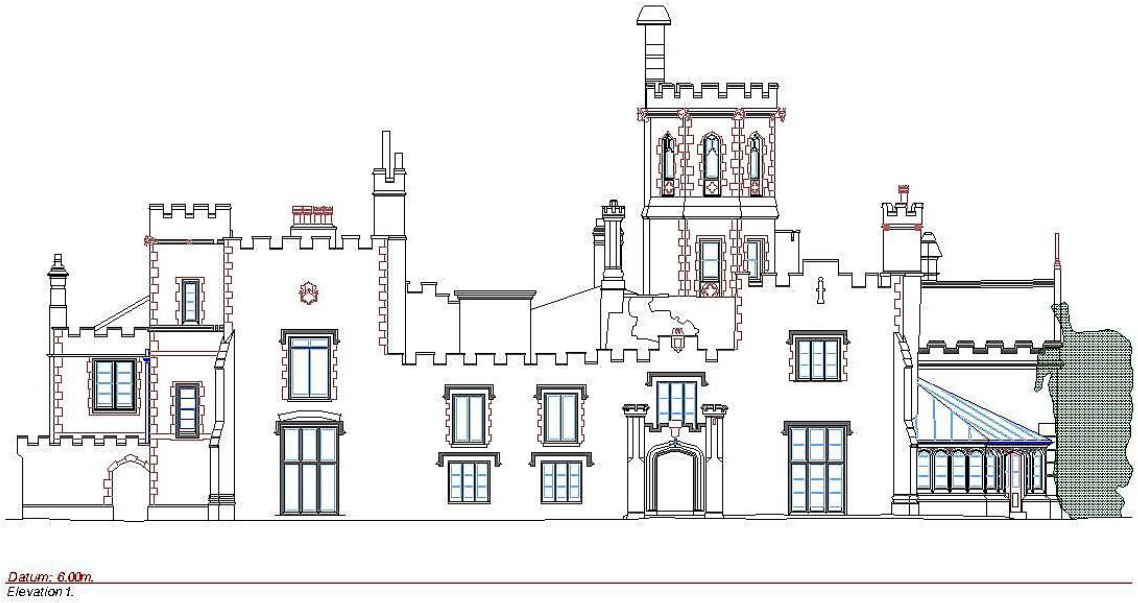


Figure 55
Uphill Manor, Weston-super-Mare, Somerset. A 2D elevation produced from the laser scan data

parallax between the two datasets. This can cause some registration problems, especially at close range. The imagery is used not only for a good-quality rendered 3D model but also for the production of ortho-images of a topographic landscape or a building elevation, for example. Ortho-images or orthophotographs are an image-based 2D output that have all perspective removed and are equivalent to an image map. They are also produced as an intermediate product to provide the base data for CAD or GIS feature collection.

Three-dimensional geometric models can also be used to generate high-quality still or animated scenes. Movies are often successfully used to present what would otherwise be large quantities of data requiring specialist viewing software and hardware. While such animations do not provide an environment through which a user can navigate freely, they do serve a useful purpose in presenting an object, site or landscape to a non-specialist group. The models generally include the use of image textures. This textural information can often help to enhance visually what may be quite a low level of geometric detail or, conversely, serve to minimise the number of mesh triangles to reduce file sizes.

2.2.6 Vectorisation

Plans, profiles, sections and elevation drawings can be generated by using the scan data as a base for tracing features. This process is also known as vectorisation and can be conducted directly from the point cloud, from the mesh with an image overlay or from ortho-images. However, if this is carried out by a surveyor or CAD operator it will be one interpretation of the data and may not include the subtleties that can be provided by the expert interpretation of, say, an archaeologist or conservation specialist. There has to be a compromise at this point, as the trained and experienced CAD operator can extract the basic metric data and some level of interpretation very efficiently, while the archaeologist will provide a fuller interpretation of the data but is likely to take significantly longer with, therefore, a cost implication. The surveyor and the end user of the data should work closely to produce an agreed specification and division of work, and be

guided by the advice and specifications provided by organisations such as Historic England and Historic Environment Scotland (see section 7).

Segmentation and classification of the point cloud is usually the first step in manual and semi-automated workflows. For example, slicing the point cloud to produce horizontal and vertical sections allows a clearer picture of the floor plans and elevations of buildings, respectively. They delineate the boundaries sufficiently well for tracing CAD data to build up a 3D vector model of the building. The feature collection process requires significant skill and experience but the main advantages are that the data becomes an intelligent attributed dataset that can be queried, analysed and accessed easily by most end users. The vectorisation process also produces file sizes that are significantly smaller than the point clouds and meshes, and 2D drawings remain the product of choice for most architects, archaeologists and conservators (Figure 55).

Manual feature collection is slow and labour intensive and attempts have been made to semi-automate the process. The goal of full automation is a difficult one, as the differentiation of features can rest on very subtle changes in surfaces or materials. The completion, identification and attribution (the non-metric intelligence) of those features will probably remain the domain of the expert for the foreseeable future. A good example is the extraction of stonework on a heritage building (Figure 56). The accumulation of moss and lichen and frequent repointing exercises present even the most experienced human analyst with difficulties in delineating the masonry. Automated shape, plane and edge detection methods using, for example, region growing and variations in contrast, intensity and range have been studied. Most research has concentrated on the automation of feature extraction from airborne lidar, and a comprehensive review of the techniques for building detection in urban studies is described in Tomljenovic *et al* (2015). Most studies rely on a combination of scan and image data.

Figure 56
Vectorisation of the full detail from an ortho-image showing how difficult it can be to interpret the edges of the stonework

Laser scan processing software now includes algorithms for semi-automating the extraction. These can be included within the main suites provided by the manufacturers or as plug-ins to CAD or BIM software. Applications include Leica Pegasus: MapFactory for vehicle mobile mapping and ClearEdge3D EdgeWise for buildings. The latter company also provides a plug-in for Autodesk Revit so that a direct scan to BIM procedure can be implemented. This is also the case with IMAGINiT Scan to BIM. Once any semi-automated planes and lines have been extracted, additional software is available, such as the FARO PointSense Family, to clean, align, extend and connect the polygons and lines. These are labour-saving devices but still require manual intervention to produce fully attributed CAD and BIM data.

2.3 Data management

2.3.1 Data viewing

Some laser scanner manufacturers offer software that enables the point cloud and associated image data to be available via the internet for viewing by the client or other stakeholders in a collaborative venture. The streaming of just the on-screen data at an appropriate level of detail allows interactive interrogation for basic

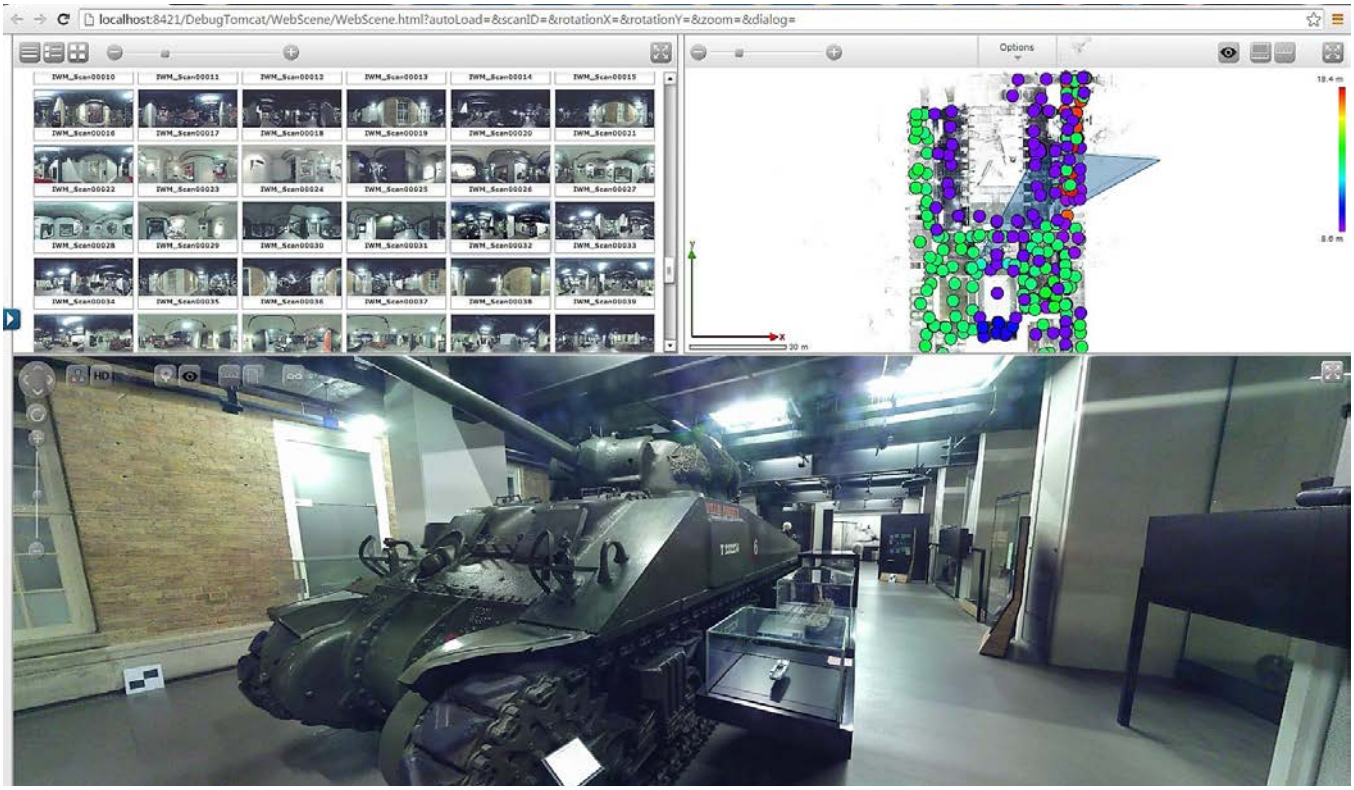


Figure 57
Imperial War Museum, London. An example of a web-based viewer: FARO WebShare
© Stanburys Ltd

analysis and measurements with just a plug-in to a browser (Figure 57). Although the software is usually free, the data provider may want to charge for the data handling and server costs. Some manufacturers provide a limited version of the processing software to achieve the same solution on locally stored data. The latter method requires the necessary storage space and the processing power to manipulate the data. Some examples of data viewers were given in section 1.3.3 but the list is repeated here for convenience: Leica TruView Global, Trimble RealWorks, FARO SCENE LT, FARO WebShare Cloud, RIEGL RiSCAN PRO (viewer licence), LFM NetView and Topcon ScanMaster.

2.3.2 Data re-processing

Throughout the procedures described in section 2.2 a succession of datasets is produced. As well as the raw point cloud and image data, there are the processed point clouds and meshes, enhanced images, panoramas, ortho-images and CAD data. In a heritage context the retention of data in archives is the recommended and accepted practice and, in the case of continuous technical advances in laser scan processing, there is a responsibility to future-proof the information. New methods of analysis will become available which could take the form of enhanced multispectral or waveform analysis of the intensity, range and image data for improved material, condition or archaeological research.

Decisions have to made, however, about how much of the data to retain. If data storage capacity is not a problem then a large volume can be kept, but this will require meticulous metadata records for each stage. If space is an issue, storage of just the original point clouds and images will allow reproduction of downstream products. The processes employed and their parameters (eg registration, decimation and mesh creation)

should be fully reported to form part of the metadata for later use and archiving. Raw x,y,z,I coordinates, E57 (general purpose) and LAS (aerial) data are non-proprietary formats that will allow import and re-processing by most software suites.

There is also a responsibility on the part of the data supplier to retain project information. For any data remaining in proprietary formats the supplier should maintain the capabilities of access and conversion to universal formats. Historic England's Metric Survey Specifications for Cultural Heritage (Andrews *et al* 2015) recommends a minimum period of six years for data retention, to include field notes/diagrams and the raw, intermediate and final datasets as specified.

2.3.3 Formats

Data exchange formats, as opposed to proprietary formats, have been designed to facilitate the transfer of information between different software suites. A well-known example of this is the DXF format produced by Autodesk for their AutoCAD software. Although proprietary in origin, it has become a universal text-based or ASCII format for CAD users. For laser scan data most software packages also export and import simple text files containing x,y,z coordinates, intensity data and colour (RGB) information.

There are now two widely used formats that have originated independently of manufacturers that provide an exchange service for point cloud data and also retain more information than the simple text format. One is the LAS format that has been developed by the American Society for Photogrammetry and Remote Sensing (ASPRS). It was designed primarily for aerial lidar data but it can also be used for terrestrial scans. The other format has been developed by the American Society for Testing and Materials (ASTM) and is known as E57 after the name of the committee that devised the standard. This is a more universal and flexible system than LAS and allows for the inclusion of, for example, image data, gridded data and different coordinate systems.

The above are formats in which to store the point cloud data. For the derived products there are other exchange formats available. These should, ideally, be non-proprietary but, like AutoCAD DXF, some formats designed by software suppliers have gained widespread acceptance. The following formats (with the name of the developer, type and additional information, as appropriate) are examples of commonly used exchange formats.

For point cloud data:

- E57 – ASTM, ASCII, image data, gridded and random points
- LAS – ASPRS, ASCII, fixed record, mainly for aerial
- LAZ – a compressed version of LAS
- PTS – ASCII, unified data, one coordinate system only
- PTX – ASCII, multiple scans with transformation information for each
- TXT – ASCII, x,y,z point cloud

For triangular mesh data:

- OBJ – Wavefront, ASCII, surfaces, primitives
- STL – 3D Systems, ASCII and binary, solid model creation, 3D printing
- PLY – Stanford, ASCII or binary

For DTMs:

- TXT – ASCII text, gridded or random
- TIF – GeoTIFF, raster version

For CAD data:

- DXF – Autodesk, ASCII
- DWG – Autodesk, binary

For animations:

- MOV – Quicktime
- AVI – Microsoft, dated but common, Windows only
- WMV – Microsoft, streaming
- MP4 – MPEG

For 3D models:

- WRL – VRML, browser viewing
- X3D – successor to VRML with additional capabilities

For images:

- TIF – Adobe TIFF, large files but compressible
- TIF – GeoTIFF, georeferencing embedded or as separate TFW file, openable as standard TIFF
- JPG – JPEG, variable compression, data loss at high compression

Delivery of end-products should also include reports and metadata in PDF and text formats.

2.3.4 Metadata and archiving

An important element of any heritage project is the metadata. In this context, it is defined as a set of data that describes the survey data. It is crucial that any interested party in the future is able to understand the purpose of and the methods used in the project. Metadata should form an integral component of the information submitted to an archive such as the Archaeological Data Service (ADS). As an example of the minimum level of information that should be recorded for the scan data, the following list appears in Historic England's Metric Survey Specifications for Cultural Heritage (Andrews *et al* 2015):

- raw data file name
- project reference number (if known)
- scanning system used including serial number
- average point density on the subject (with reference range)
- total number of points
- date of capture
- site name
- list entry number (if known)
- company name

Survey reports (part of the metadata) should also be produced for each aspect of the survey (the control network, scanning, photography, modelling, etc). Metric Survey Specifications for Cultural Heritage (Andrews *et al* 2015) provides detailed information on metadata and archiving, as does ADS's Archiving Laser Scan Data (ADS/ Digital Antiquity 2009).

3 Specifying and Commissioning a Survey

3.1 The purpose of the survey

Despite the advent of lower cost systems and more user-friendly software, it is still more likely that heritage professionals will commission survey work from a specialist rather than carrying out the work themselves. The following advice may help you when considering and specifying a laser scan survey.

- Describe the purpose of the survey. Is it for archaeological analysis, conservation of the fabric, a structural survey of the roof timbers or purely for documentation prior to change? These factors will have a bearing on the methods and specification required
- Provide a little background history of the subject to provide the context for the survey
- Define the extent of the subject, the available access and any health and safety issues. These should be set out clearly in the introduction to the brief and on existing plans or elevation drawings
- Decide on the features to be shown and at what level of detail they should be portrayed. The latter may differ across a site as a result of, for example, variation in cultural significance. The level of detail selected may cause difficulty later, as the full significance of the subject may not be apparent until the survey and its analysis are completed
- Determine the end-products, which will include the information required for analysis, conservation or management tasks in the future
- Consider the scale, accuracy and content commensurate with the subject and the available budget. These considerations should also include any necessary investment in equipment and training to manage or further analyse the data
- To add value to the survey, other stakeholders may be interested and their needs could be incorporated
- It is not usually necessary to specify the techniques to be used, as these decisions should be the domain of the surveyor so long as the chosen methods and equipment are capable of producing the quality and product required

- Consider how the collected survey will be archived and made available for use in the future. Advice can be sought from national organisations such as the ADS
- Determine who will have the rights to and usage of the data at all stages of the project
- Prepare the project brief using any advice given and by consulting a standard specification such as that published by Historic England (Andrews *et al* 2015)
- Prior to the commission, the contractor should provide a method statement that conforms to the specification or outlines the reasons for any variation
- Instrument certification and up-to-date calibration reports should be requested as part of the contractor's proposal
- On delivery of the survey a quality check should be performed to ensure compliance with the specification

If you lack any knowledge of the possibilities available, consult a contractor to help specify the project. A contractor should be able to advise whether the requirements being considered are feasible technically and financially. If not, other techniques or deliverables may be suggested.

3.2 In-house or contractor survey

This is a big dilemma for many organisations: to have complete control of the outcome of a project but at the expense of time, investment and potential teething problems, versus a job done out of house but with little inside knowledge gained and a high one-off cost. If there is continuous work, setting up a survey unit should reap benefits in the long term but many projects are ad hoc and the survey may just be a small part of the overall project. The high costs of laser scanning equipment and the training required also tend to mitigate against client involvement. Hiring the hardware and software is an option, and survey companies frequently do this to temporarily add additional capacity while maintaining an efficiency advantage by using experienced staff. It should also be borne in mind that laser scanning is only part of the survey. Accompanying field data may be required in terms of survey control and photography, and the processing of the data requires skills and software that extend into 3D modelling, animation and presentation. This capacity may be absent in the commissioning organisation.

Professional organisations, such as the Royal Institution of Chartered Surveyors (RICS) and the Chartered Institution of Civil Engineering Surveyors (CInstCES), and trade organisations such as The Survey Association (TSA), should be able to assist in finding appropriate contractors. Survey company websites and the case studies they list provide an indication of their expertise. Historic England maintains a list of contractors (for their own projects) using framework agreements; national bodies, including Historic England, Historic Environment Scotland and Cadw (Wales), may be able to help with the production of a suitable specification on a consultancy basis, especially for listed buildings. Other individuals or organisations with experience of commissioning projects could also be contacted for recommendations.

3.3 Existing data sources

Prior to a survey it may be useful to establish whether any documentation already exists on the subject under investigation. It is very unlikely that they will meet any new requirements but old plans, photographs and reports can form the basis on which to design a new survey and provide valuable historic information for comparison, monitoring or just context.

National organisations (eg the Historic England Archive in Swindon, ADS in York, The National Archives and historic environment records for England via Heritage Gateway, for Wales via Historic Wales and for Scotland via the National Record of the Historic Environment), local library archives and heritage organisations are all worth approaching for contextual information.

	Scale	Effective point density	Precision of measurement
Close-range	1:5	0.5mm	0.5 mm
	1:10	1.0 mm	1.0 mm
Terrestrial	1:20	2.5 mm	2.5 mm
	1:50	5.0 mm	5.0 mm
	1:100	15.0 mm	15.0 mm
Aerial	1:200	30.0 mm	30.0 mm
	1:500	75.0 mm	75.0 mm

Table 2
Laser scanning accuracies and resolutions at different scales
After Andrews *et al* 2015

Architects and survey companies in the heritage field may also have data on past projects at the same site. As an example, the Plans Catalogue for Fountains Abbey, North Yorkshire (part of the Studley Royal Park and including the ruins of Fountains Abbey, a World Heritage Site) lists approximately 1,000 items in the Historic England Archive (formerly the National Monuments Record). These consist of plans, sketches, elevations, sections, deeds and reports and date from the 1870s to the current day.

3.4 Scale of the subject

The size of the object or site should be used to help define the appropriate laser scanning regime.

- For artefacts, building fragments and small statues, for example, where sub-millimetre resolution and accuracy is required, a triangulation laser scanner would probably be the best option
- For an *in situ* building feature or larger statue, a triangulation, pulse or phase-comparison scanner may be appropriate, and the decision about which to use may have to be based on ease of access, as triangulation scanners are more accurate at close range
- For a building or a building elevation, a pulse or phase-comparison scanner would be more appropriate
- For larger sites and to include the surrounding topography, a 360° pulse scanner or SUA survey should be considered
- For an entire landscape, perhaps incorporating a number of sites of interest, traditional airborne or SUA survey would probably be the most suitable method

3.5 Accuracy and resolution

The most obvious factor in designing a survey using a mass data collection technique is ensuring that the information required is actually discernible in the dataset. This is the case for both laser scan and photographic data, and is determined by the point cloud density and pixel size, respectively. A general rule of thumb is that the point density or resolution should be better by a factor of two than the smallest feature to be identified. There is little to be gained by having a resolution significantly better than the accuracy of the equipment as no reliable information will be gathered. The accuracy should, at the very least, be equivalent to the resolution. For example if a resolution of 2.5mm is required, an instrument with an accuracy of 2.5mm or better should be used. For various scales of deliverable product, Historic England (Andrews *et al* 2015) has established a standard resolution table for laser scan data (Table 2).

When assessing the resolution and accuracy, it may be that some intricately carved objects require a more detailed survey and other areas, for example a featureless wall, require only a very low resolution to provide basic outlines. This should be incorporated into the design so that each area is surveyed appropriately within time and budget constraints.

A good example of the resolution of aerial lidar is shown in Figure 58. This image compares the information available at 2m and 1m resolutions. Selective areas of the UK are available at 25cm and 50cm resolutions from the Environment Agency (see section 7.5).

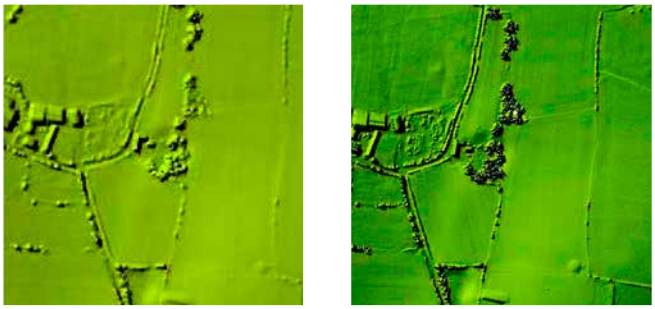


Figure 58
A comparison of 2m and 1m resolution lidar data showing the significant increase in information available to the analyst

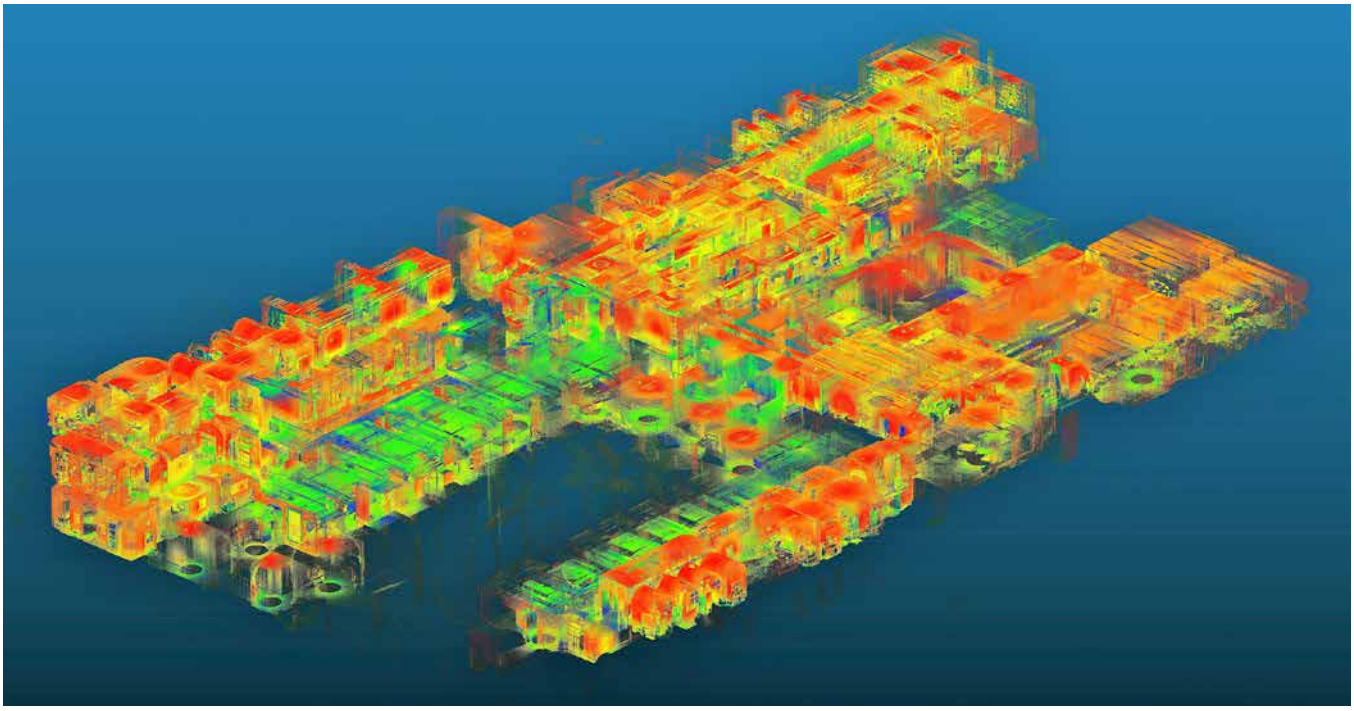
Image from Crutchley and Small (2016, Figure 11)

3.6 Georeferencing

The use of survey control on a project can have two objectives. The first is to provide a network of accurate points so that the point clouds can be successfully unified into a common coordinate system. Registering using cloud-to-cloud techniques can be very successful (see section 2.2.2) but around a building, for example, or where it is difficult to maintain a good overlap, control becomes essential. It also provides certainty and, with some redundancy in the network, an estimate of the overall accuracy. As an example, the only practical method of unifying the hundreds of scans taken to survey the interior of the Imperial War Museum in London was to use an accurate control network (Figure 59).

The second possible objective of survey control is to relate the network for the subject to either a wider site system or a national grid and height datum. A very accurate site system can provide the basis for long-term monitoring or structural analysis. For surveys of landscape a network related to the national system can also provide a monitoring service over a wider area. The georeferencing of found artefacts, barrows and structures can lead to studies of their spatial relationship and more extensive archaeological analysis.

If successive scans of an archaeological site are taken as the excavation progresses, the control can act as a framework within which the point clouds are placed. In this way an accurate 3D model can be built up of the underground spatial relationship between artefacts, bones, deposits, etc, which can provide invaluable information for the analysis of a site.



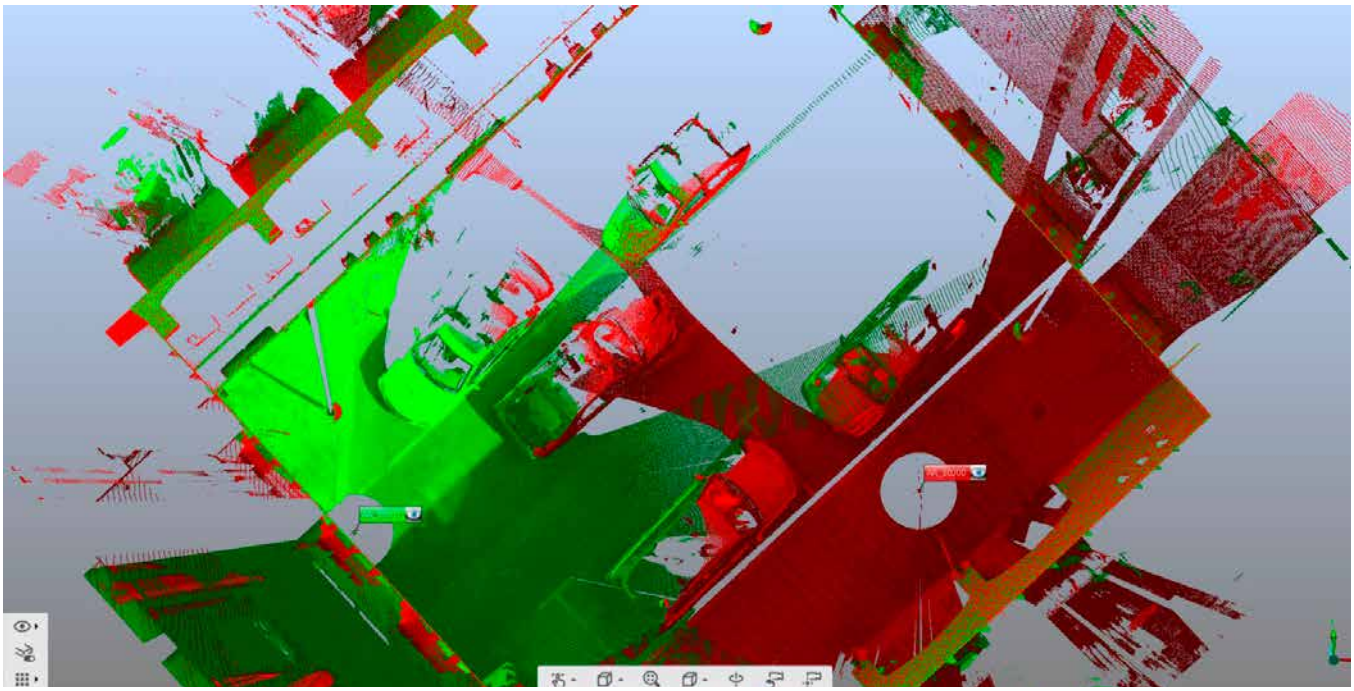


Figure 59 (top)
Imperial War Museum, London. An overview of the hundreds of scans taken to survey the interior of the museum. The scan locations are shown by circles
© Stanburys Ltd

Figure 60 (bottom)
Careful consideration of the scan locations is required to avoid obscured areas (grey)
© Clive Boardman

Figure 61
The interior of Gibside Hall, Tyne and Wear (National Trust). A good example of the need to assess a site with the client prior to finalising the survey specification
© Clive Boardman

3.7 Site conditions

There can be enormous variation in site conditions and a full appraisal should be made by both the client and the contractor prior to the survey. There may be:

- health and safety considerations, such as unsafe buildings or the presence of asbestos
- limits on access, for example because of public presence or tidal conditions at a coastal site
- location difficulties, such as a castle on a hill, on the edge of a cliff or surrounded by a moat
- time constraints, such as scanning to take place at regular intervals to monitor an excavation, equipment availability or scanning only at night
- adverse weather conditions, for example rain and dust affecting the equipment or wind affecting stability
- obstructions, such as people, vegetation or vehicles. In Figure 60, careful consideration of the scan locations is required to avoid obscured areas (grey) caused, in this case, by parked cars. Two diagonally placed positions would normally be sufficient if it was free from obstruction but with the presence of the vehicles a scan at each corner is required

Usually solutions or work-rounds to most issues will present themselves, even if location difficulties can test the ingenuity of the surveyors. SUAs can provide an answer, although SUA-mounted laser scanners are still rare and may not provide the quality of data compared with ground-based scanners or photogrammetric methods. Long-range scanners or those mounted on very stable scaffolding platforms may be preferable. Regular monitoring of an excavation will require close liaison between the contractor and the site staff to ensure there are personnel and equipment availability at the right time. Trees and other vegetation are very common obstructions and if they cannot be pruned back surveying may need to take place when at least the deciduous vegetation is free of leaf. Most outdoor laser scanners are now protected to IP54 level (this is an International Protection mark and IP54 signifies that the equipment has limited

protection against dust ingress and can withstand splash water from any direction). However, if water or dust settles on the rotating prism or cover, for example, the quality of the scan data will be affected. It is worth reiterating that site conditions are significant factors in the potential success of a project and experience is needed to investigate any difficulties thoroughly prior to a commission (Figure 61).

3.8 End products

The provision of 3D model outputs or 2D drawings requires quite different fieldwork and data-processing regimes. 2D drawings may require a great deal of effort within CAD software to trace architectural features and stonework but the fieldwork is generally more straightforward, usually scanning orthogonally to a building elevation. Fieldwork for 3D modelling is often more complex as all facets of a structure need to be covered to maximise the completeness of the model. In the office the production of a 3D model may not be as labour intensive as a 2D drawing, if, for example, only a textured mesh is the required deliverable. However, most projects are not quite as clear-cut as these examples, so careful consideration has to be given to the final dataset when designing the fieldwork campaign. Potential products derived from laser scan surveys include:

- point cloud – raw, cleaned, registered, decimated, classified, intensity mapped, colourised
- triangular mesh model
- textured mesh model – plain or photographic
- panoramic imagery
- ortho-images
- DTM and DSM
- CAD data – plans, elevations, sections, models
- BIM
- control network
- additional photography

The level of detail required is a critical discussion that needs to take place between client and surveyor and has a significant bearing on the cost. It is of particular concern for BIM projects as it can be an extremely labour-intensive exercise to produce a full set of parameter-based information compared with CAD data, especially for historic buildings. The shape and status of the components of a historic building (incomplete or deformed walls, statues, carvings, etc) do not always lend themselves to the more rigid presentations of BIM. For example, for the survey of a Category B-listed neo-classical Victorian former post office in Dundee, Dundee and Angus, the client specified that two winged statutes had to be included in the BIM product as they were an important part of the cultural significance of the building. The solution to providing the high level of detail required for the two statues was to import meshes of them (derived from the scan data) into the model. Although not strictly BIM components, the rendered meshes provided the completeness required (Figure 62).

Clients also have to consider whether they have the capacity and ability to manage and use the requested deliverables. The contractor may be able to advise, supply the equipment or train the customer in the use of the data.

On discussion with the client, laser scanning may not in fact be the best method to use. However, many contractors that have invested in the equipment find it can be time saving even if the final product is a set of outline drawings. The point clouds can be used to help control a conventional measured building survey and integrate the hand-measured components. In this instance the point cloud may only partly cover the subject but it may still provide a useful deliverable.

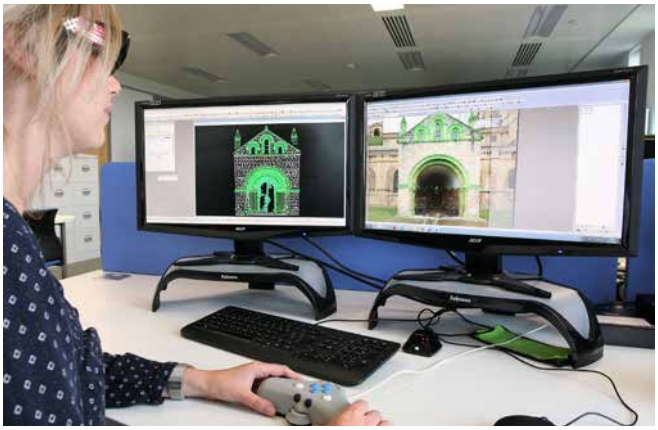
Figure 62
The old post-office, Dundee, Dundee and Angus. From the left: point cloud, mesh and as part of the rendered model
Courtesy of the Greenhatch Group Ltd and Page Park Architects

3.9 Budget

Laser scanning is a high-value process and the budget required may not always be available. However, the higher costs may be justified by the wealth of point cloud and photographic information collected, especially if other stakeholders in the project can provide input to the specification and gain access to the data. Also, there may not be a viable alternative. For example, if surfaces are required for deformation studies and there is little surface texture, photogrammetric methods may not be suitable. Using the scanner or scan data for other tangential projects can help to spread the investment costs (see section 3.8), perhaps making the service cheaper or assisting with the decision to invest, especially for a larger heritage organisation.

3.10 Alternative methods

An essential part of the decision-making process, after deciding on the end products and prior to commissioning, is to determine whether there are alternative methods of achieving the same goals. Laser scanning or any mass data collection method may be overkill when basic plans, sections or elevations are required. These may be better served by TST, levelling and hand measurements with a photographic backup. There is also an argument that, if simultaneous interpretation is required by the architect, conservator or, more commonly, the archaeologist, then basic measured survey should be part of the parallel thematic survey. However, this argument begins to break down if more metric detail is required and the archaeologist spends more time surveying than interpreting. These types of survey may be localised but they can also be tied into a common site network, especially on archaeological excavations.



A small topographic survey using kinematic GNSS or a total station may produce a lower cost site plan but over a large area it will become a less efficient method. These are also selective techniques, with the surveyor choosing what to survey and, possibly, missing detail that may not have been required at the time but could prove useful in a later analysis.

For mass data collection the main alternative is digital photogrammetry. The techniques differ in that laser scanning records its own transmitted light reflected back from a surface whereas photography records light reflected from surfaces illuminated by sunlight or artificial lighting. They are termed active and passive methods, respectively. Photogrammetry has been the domain of specialist organisations because digital stereo workstations are expensive and require highly skilled operators who can collect vector data very efficiently. These factors have precluded casual use of the method by end users. Globally, most aerial mapping and some terrestrial surveys are still produced by stereo methods and contractors are available to advise clients if this is the best method to use, for example if vector mapping into CAD or GIS is the main product required. Figure 63 illustrates a DAT/EM Summit stereo workstation with twin screens, a 3D cursor and active stereo eyewear. This is a common setup for both aerial survey and terrestrial projects.

Figure 63 (top left)
A DAT/EM Summit photogrammetric workstation. The operator is using stereo eyewear and a 3D cursor to trace architectural detail of a church facade
© IIC Technologies Ltd

Figure 64 (centre left)
An image-textured 3D model produced using SfM software PhotoScan by Agisoft LLC. The positions of the photographs are shown
© Clive Boardman.

Figure 65 (bottom left)
An ortho-image from the same model as Figure 64 output at 1mm pixel resolution
© Clive Boardman

A more direct comparison with laser scanning is the newer automated technique known as multi-view photogrammetry or structure from motion (SfM). The integration of computer vision algorithms that automatically and efficiently match the adjacent images has led to the development of user-friendly software at a much lower cost than traditional photogrammetry. The matching process produces point clouds that can be compared favourably with laser point clouds. However, the lighting conditions are more critical as it is a photographic technique and the surface needs a good texture (tonal variation) for the matching algorithms to work successfully. The advantages are that no specialist equipment is required, site time can be very short, people are comfortable using cameras, access to difficult areas is easier and mesh rendering uses generally higher quality photography compared with that taken by laser scanners. Figure 64 illustrates a 3D model of a statue produced (in Agisoft PhotoScan software) from six images with their relative locations indicated. The DSLR imagery was used to produce a 1mm resolution ortho-image, which can be seen in Figure 65.

With regard to SUA surveying, the use of on-board cameras is commonplace compared with lidar systems and very lightweight cameras can operate on low-cost SUA. When considering data acquisition for SUA or full airborne systems, a major advantage of lidar is that it is able to measure through forest canopies. This is not the case with photography, as frames are taken at less frequent intervals than the time it takes for one revolution of the scanning head. The successive views from the camera are, therefore, much different and penetration to ground through a small gap by two adjacent images is unlikely. In most cases, the analysis of the full waveform in a lidar system allows mapping of the woodland structure as well as recording the last signal to ground.

There are many papers published on the comparison between laser scanning and SfM photogrammetry; Chandler and Buckley (2016), albeit from the perspective of geosciences, provides a concise description and summary of the techniques. Sou (2016) compares the two techniques for the analysis of carvings and graffiti at Carlisle Castle, Cumbria.

Allowing ourselves to look into the future of these rapidly advancing technologies, what can we expect to see for active 3D data collection and processing? It only takes a little imagination to predict the development of an instrument that employs several multi-channel high-resolution ToF cameras and associated projectors/trackers with on-board IMU, GNSS and SLAM algorithms. It will include a high-resolution multi-lens colour video camera system to produce instantaneous 360° panoramas that will be combined into a real-time and growing 3D model as the surveyor walks around a historic site. The instrument would be solid state, lightweight and capable of being mounted on an autonomous clash-detecting SUA. Advanced learning segmentation and classification algorithms will automatically detect, identify and model all visible features to produce a building or site information model. We could then instruct the SUA to deliver the model directly to the client!

4 Case Studies

Case Study 1: Martins Bank – scan to BIM project

Type: pulse and phase-comparison scanning, HDR imagery

Keywords: refurbishment, levels of detail, BIM, data viewing

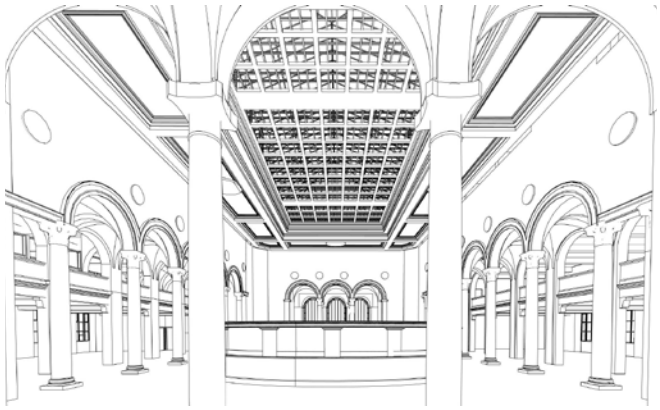


Figure CS1.1 (top)
Martins Bank: the model of the exterior
© AHR

Figure CS1.2 (bottom)
Martins Bank: the model of the interior
© AHR

Introduction

Martins Bank, Liverpool, Merseyside, is a building steeped in history; one notable use being that it became the national gold store during the Second World War. The building was completed in 1932 and currently has Grade II-listed status. There are areas within the building that hold special significance within the listing: the banking hall, the atrium skylight, the heating system and the chairman's office and boardroom. This complexity required a survey team with a strong heritage pedigree.

Soon after acquisition of the building, the client approached AHR to discuss a survey for restoration and refurbishment purposes. It was decided from the outset that a building information modelling (BIM) workflow would be adopted and all the consultants in the project chain should have the relevant experience.

Instruments and software

As any survey is only as good as the control it is based on, a closed-loop traverse was set up externally using Leica total stations. An individual traverse was then created on each of the 12 floors and linked back to the external traverse using the same instrumentation. This provided a fully connected three-dimensional (3D) network allowing checks to all observed points. The next step was to place and coordinate reference targets throughout the areas to be scanned. Three FARO Focus3D X 330 laser scanners were then used to capture the internal data using the pre-positioned targets for reference. For the exterior, a Leica P40 was used because of the oblique lines of sight, high level of detail and the need to set up from a distance. Finally, an NCTech iSTAR camera was used to obtain high dynamic range (HDR)

imagery for colourising the point cloud. This also proved to be time saving compared with using the scanner's on-board cameras.

Why was scanning selected?

No other method of surveying captures the environment as completely as laser scanning. If used correctly it provides levels of data and accuracy in a rapid timeframe. In this case it was also important that flexibility in the field was maintained as the survey brief was continuously evolving, with levels of detail specifications changing on a daily basis. Scanning achieved this in the data-processing phase without the need to revisit areas already surveyed. The resolution of the point cloud also provided the ability to build individual component parts for many of the model elements. In simple terms, items were no longer singular objects but a compilation of the parts used to construct them. This information enriched the model and helped give a higher return from the BIM workflow. The Leica TruView and FARO SCENE web portals were also an invaluable resource for the design team, whose timeline did not allow them to wait for the completed model.

What problems were encountered?

The most obvious challenge was the logistics. The project required around 3,000 individual scans, each of which had to be registered and audited against the survey control. Survey creep is a concern when working with a high volume of scans, hence the need for an extensive and robust survey control network. Another problem was the large dataset. AHR had the latest high-end graphics machines but was aware that the client may not have this kind of processing capability. This is often overlooked and clients can be handed datasets they cannot access let alone use. Decisions had to be made as to how much decimation of the point cloud was acceptable for the client's needs. As the raw data was retained for the 3D Revit model there was always the option of providing a greater resolution point cloud to the client should it be required.

What was the deliverable output?

As the project had to follow a BIM workflow from the beginning, the final deliverable was a 3D Revit as-built survey model. Two-dimensional (2D) information was then extracted from the model in the form of drawing sheets, plans, sections, elevations, etc. The size and detail of the model was a constant source of debate. AHR suggested that the model should have simplified 3D shapes to aid daily usage. The 2D outputs were supplemented with high-level detailing to ensure they were fit for planning and record purposes. The information and access to it are the most important elements of any BIM project. With this in mind, the model contained some general metadata that allowed basic scheduling activities for walls, windows, doors and floor areas, along with the relevant industry standard classifications to aid the design team. A colourised point cloud was also provided to the client as part of the suite of deliverables.

Case Study 2: Rhineland – countermarks on Roman coins

Type: structured light triangulation scanning

Keywords: coins, Roman, morphometric

Introduction

This study was focused on the analysis of countermarks ascribed to Publius Quinctilius Varus, the Roman commander-in-chief and legatus Augusti pro praetore in the province of Germania magna from 7 to 9 AD. He is famous for his death and the loss of three legions during the Battle of the Teutoburg Forest in 9A D.

A total of more than 600 copper coins (asses) bearing a stamp with the initials VAR has been uncovered in Roman sites, mainly in the Rhineland area of Germany. This countermark was probably applied on older coins on the occasion of small donations to the troops and only circulated at a local scale. Comprehensive studies of these countermarks have established the existence of different countermark dies that must have been in use between 7 and 9 AD. Identifying individual dies and traces of ordering them by means of increasing use-wear may offer new insights into this time period and the movement of troops.

Instruments and software

Three-dimensional (3D) scanning was performed on 37 coins using an AICON Breuckmann smartSCAN-HE R8 (75mm field of view, 8MP). Fringe projection was performed by blue light LEDs at a wavelength of 460nm to minimise reflectance from the metallic surface. Using the proprietary software AICON OPTOCAT, the final digital models yielded a spatial

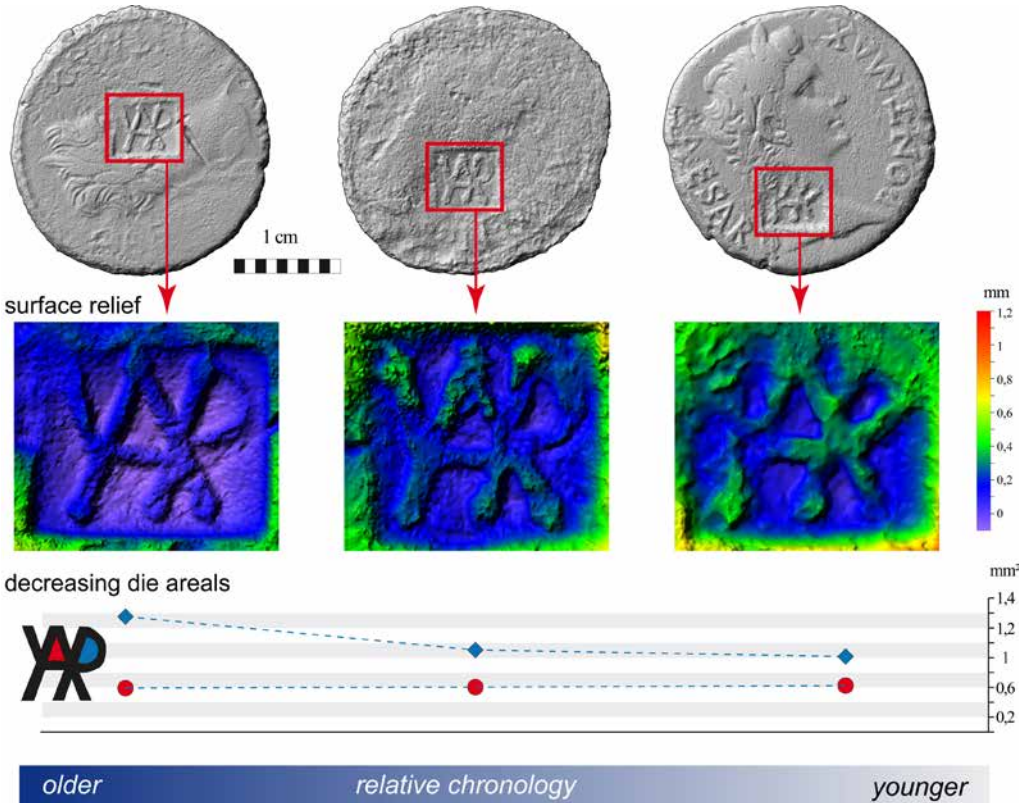


Figure CS2.1
Coin stamp comparison showing increasing wear of the stamp
Courtesy of the Archaeological State Heritage Office of Saxony, Dresden

resolution of 29µm. Grey-scale shaded relief images were produced in TroveSketch to meet the requirements of archaeological object presentation. The software Surfer (by Golden Software) and Autodesk AutoCAD were used to measure distances, imprint depths and areas. For a morphometrical assessment the R package geomorph was used to run a generalised Procrustes (shape and shape distribution) analysis based on a chosen set of 3D landmarks.

Why was scanning selected?

Detailed morphometrical analyses of ancient coins can support the reconstruction of the life cycles of individual coin dies. Based on the identification of re-cutting and use-wear features, they provide insights into technological procedures and can help establish a chronological order within coin series. However, the recording of coins is traditionally based on either 2D documentation (photo, drawing, rubbing) or plaster casts, which limits the detailed measurements and statistical comparison possible between coins from different collections. High-resolution 3D scanning provides the advantage of precise measurements of areas, imprint depths, small distances and the recording of 3D landmarks.

What problems were encountered?

The shapes of the countermarks were affected greatly not only by secondary damage but also from phases of re-cutting and modification during the life cycle of the die. Moreover, the orientation of the die imprints had to be done manually with the lowest point as the base and the lower edges of the letters for horizontal alignment. Therefore triangular mesh-to-mesh comparison was rejected in favour of a statistical approach based on 3D landmarks, in order to identify the countermarks from different dies quickly. Further statistical analyses of the letter width and imprint depth provided valuable information about the intensity of use-wear and re-cutting. However, careful visual assessment was still necessary to sort the imprints from the oldest to the youngest.

What was the deliverable output?

High-resolution 3D models of the coins together with standard deliverables (greyscale shaded reliefs of the obverse and reverse surfaces) were handed over to the collections holding the coins and will be available for further studies. Standard PLY format files of the countermarks are available as supplementary material to the publication that presents the detailed workflow.

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Tolksdorf, JF, Elburg, R and Reuter, T 2017 ‘Can 3D scanning of countermarks on Roman coins help to reconstruct the movement of Varus and his legion’. *Journal of Archaeological Science Reports* 11, 400–410

Case Study 3: The Parthenon Frieze – comparative 3D scanning of the original sculptures and historical casts

Type: structured light triangulation scanning

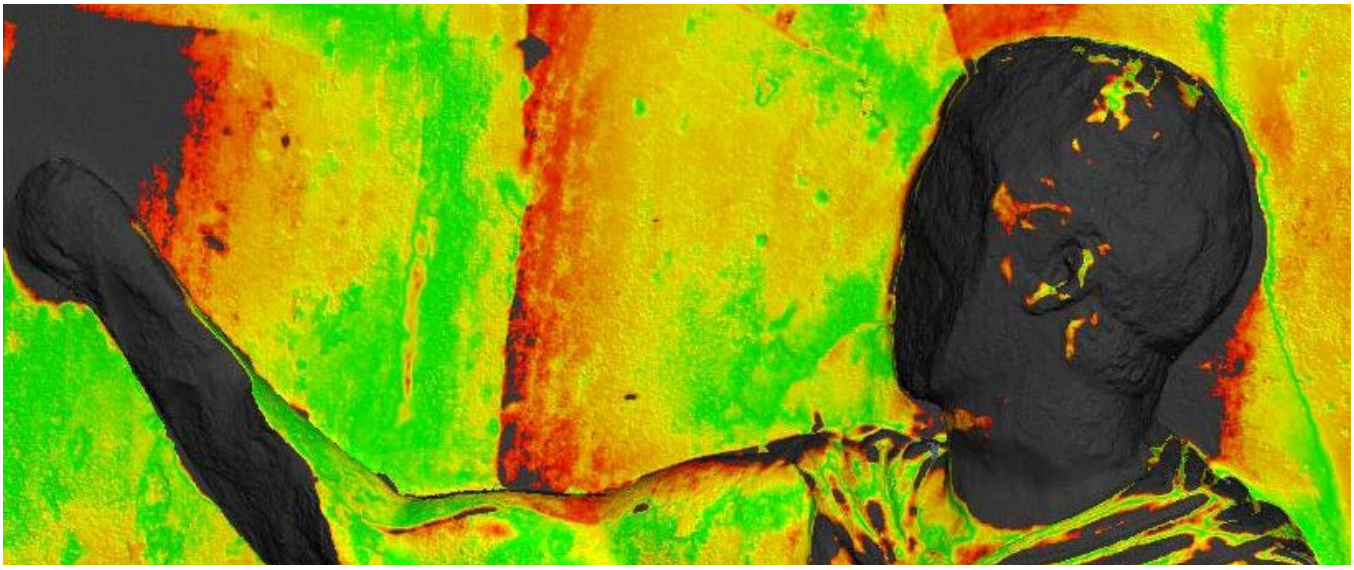
Keywords: sculptures, casts, preservation, Acropolis, British Museum

Introduction

In the early 19th century, archaeologists popularised the method of taking plaster casts to record important but vulnerable ancient sculptures *in situ*. The marble sculptures of the Parthenon, Athens, Greece, were some of the earliest to be documented in this way, first by the French archaeologist Fauvel (1753–1838) and then during the campaign of the British ambassador Lord Elgin (1766–1841). The original pieces of sculpture removed by Elgin, as well as his moulds and casts, were acquired by the British Museum in 1816. However, large sections of Parthenon sculpture, including the West Frieze, remained on the monument and were exposed to weathering and vandalism until the later 20th century. The 19th-century casts now have great

Figure CS3.1 (top)
3D image of the plaster cast for figure 23 of the Parthenon West Frieze XII

Figure CS3.2 (bottom)
The coloured deviation map overlays 3D data from the cast onto the original sculpture



archaeological significance as documentary records of the condition of the sculptures at the time of moulding. However, they are also illustrative of 19th century craft practice. Their role as documentary records depends upon their accuracy, which is connected with the practices of the plaster craftsmen (formatori). For instance, there is evidence that the formatori sometimes doctored the casts so that a damaged sculpture would appear complete (Smith 1910, 59; Jenkins 1990, 113).

Instruments and software

An AICON-Breuckmann smartSCAN-HE was used to scan the originals and casts. The scanner configuration comprised two monochrome cameras (4MP), a field of view of 400mm, and a working distance of 1m. Using the software AICON OPTOCAT, the scans were aligned, merged and converted into a PLY file to save the 3D data, together with surface normals and texture coordinates. Deviation maps of the 3D models of the originals and casts were created to calculate the closeness with which the casts reproduced the originals and to highlight fine topographical differences often not easily observable to the naked eye. Autodesk Meshmixer was used to calculate Gaussian and mean curvature to characterise surface roughness, in order to help identify clay additions made by the formatori.

Why was scanning selected?

Comparative 3D scanning was used to establish (1) the accuracy of the casts, (2) their potential to preserve sculptural features since worn away from the originals, and (3) the interventions made by the formatori. Corresponding areas of the historical casts (British Museum) and original sculptures (Acropolis Museum) were scanned (Figures CS3.1 and CS3.3). The two sets of 3D models were then mapped onto each other to identify and analyse differences. The coloured deviation map in Figure CS3.2 overlays 3D data from the cast onto the original sculpture. The red and grey highlight areas display the most change. This shows that the cast preserves substantial areas now lost from the original. The coloured deviation map in Figure CS3.4 overlays 3D data from the original sculpture onto the image of the cast. This clearly locates the boundaries of an addition made to the original sculpture by the formatori

The results demonstrated that the majority of the casts reproduced the originals even more accurately than expected, typically well within a millimetre. The analysis revealed that the casts did preserve elements lost from the originals, including both fine surface workings and larger features. The results also showed, however, that there were a number of areas within the casts that had been subject to alteration by the formatori, most likely with clay additions during moulding. While still requiring a good deal of interpretation, the 3D models, deviation maps and textural analysis helped in the identification of those areas. Therefore, the 3D analyses emphasised the complexity of the historical casts. They presented a combination of areas moulded directly from the original and areas altered by the formatori, but the casts certainly preserved lost archaeological information pertaining to the originals, and 3D scanning helped to retrieve this data.

What problems were encountered?

The specular nature of the marble originals made them harder to image effectively compared with the plaster casts. However, it was found that the surface workings still extant on the originals were more clearly captured and easier to study in the 3D models of the casts. A great deal of data interpretation was required but the combination of 3D models, deviation maps and textural analysis helped in the identification of areas of alteration.

What was the deliverable output?

Two sets of 3D models and the corresponding colour deviation maps between the original sculptures and the casts formed the deliverable output.

Figure CS3.3 (left)
3D image of the plaster cast for figure 30 of the Parthenon West Frieze XII
© Emma Payne courtesy of the Trustees of the British Museum

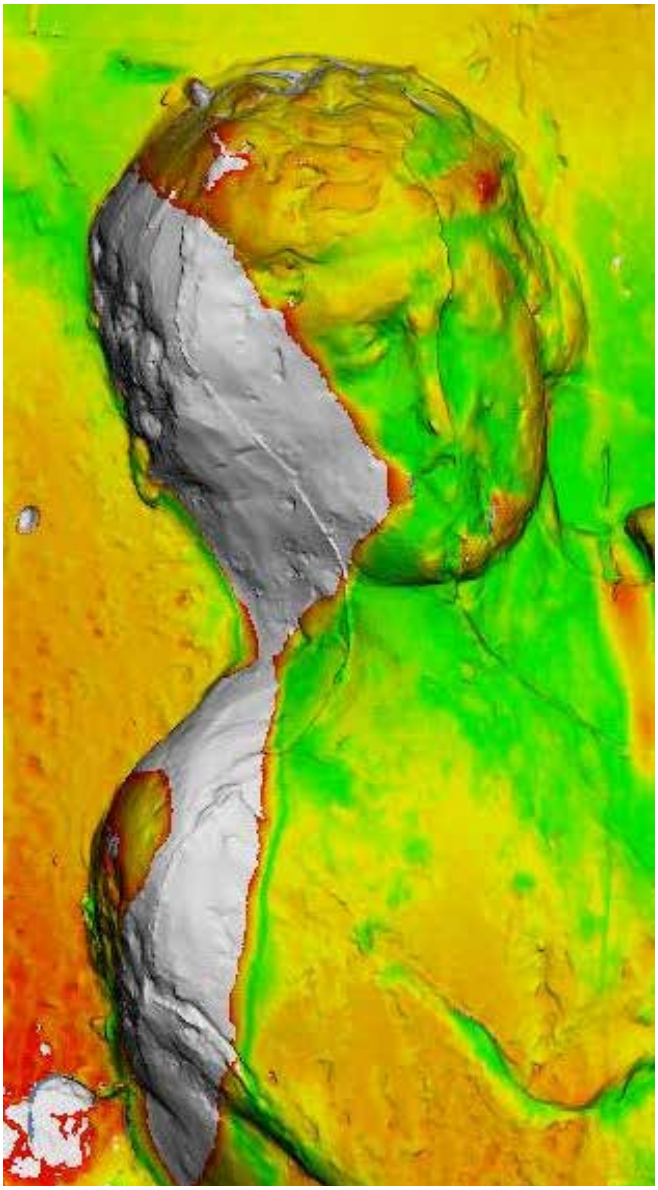


Figure CS3.4 (right)
Colour deviation map that clearly locates the boundaries of an addition made to the original sculpture by the formatori
© Emma Payne courtesy of the Trustees of the British Museum

References

Smith, A H 1910 *The Sculptures of the Parthenon*. London: British Museum

Jenkins, I 1990 'Acqui sition and supply of casts of the Parthenon sculptures by the British Museum'. *The Annual of the British School at Athens* 85, 89–114

This project formed part of Emma Payne's AHRC-funded PhD 'Cast from the antique: revealing hidden archaeology' at the Institute of Archaeology, UCL. Training and use of the smartSCAN-HE was provided courtesy of the Bernd Breuckmann Award of AICON 3D Systems.

Case Study 4: Cast Cantabria – rock art in El Mirón Cave

Type: structured light triangulation scanning

Keywords: Palaeolithic, caves, rock art, engraving, scan settings, morphology

Introduction

El Mirón Cave is located in Ramales de la Victoria, Cantabria, Spain. It was discovered in 1903 but has been largely ignored since then, despite being adjacent to the well-known cave art sites of Covalanas and La Haza. Systematic excavations conducted by Straus and González-Morales since 1996 have uncovered a long, rich cultural sequence extending from the late Middle Palaeolithic to the Middle Ages, but the most important part of the sequence is the series of levels pertaining to the Magdalenian–Azilian cultural complex during the Late Last Glacial. It is to this period that the engraved block relates. There is an accumulation of linear engravings on the block, which had fallen from the cave ceiling onto a Lower Magdalenian layer, which was covered by later Magdalenian deposits. The block had landed in a position tilted at an angle orientated toward the cave mouth, such that sunlight reaches it at the end of the afternoon during the summer. It was painted red, apparently in relationship to the secondary burial of c 100 ochre-stained bones of a young adult human in sediments also impregnated with red ochre. Radiocarbon assays of levels pre- and post-dating them place the engravings at c 16,000–13,000 BP. Although non-figurative, these engravings are among the most precisely dated yet known for the European Upper Palaeolithic, rivalled only by such sites as Le Placard in west-central France and Ambrosio in southern Spain.

The ultimate goal in documenting the rock art was to provide new information and a better understanding about the engravings in an archaeological context. A set of engravings from El Mirón Cave was chosen as an optimal test case for non-invasive three-dimensional (3D) scanning and analysis.

Instruments and software

The 3D data was collected over 1.5 days using a close-range 3D structured light scanner. The scanner used was an AICON Breuckmann provided by IMF-CSIC (the Humanities Research Centre of the Spanish National Research Council in Barcelona) with a 90mm field of view (FOV). This provided the highest resolution available for this scanner at 50µm. The 150mm and 450mm FOVs (90µm and 280µm, respectively) were additionally used to test their efficiency. The scanner had a 1.4MP camera, but current cameras of 8–16MP would allow for higher resolution or greater coverage in a single scan. AICON OPTOCAT software was used to acquire and process the 3D data. Rapidform (now 3D Systems Geomagic) and MountainsMap (Digital Surf) were used to analyse the data.

Why was scanning selected?

The palimpsest nature of some rock art is a hindrance to the analysis of their motifs. Conventional methods based on drawings, photographs or light/shadow relationships are insufficient. A more efficient way to detect certain features and characterise ‘engraving groove families’ is by distinguishing the morphologies of strokes. The main goals were (1) to test and analyse to what extent different scanner resolutions determine the detection of

Figure CS4.1
El Mirón cave: the 3D scanning workspace

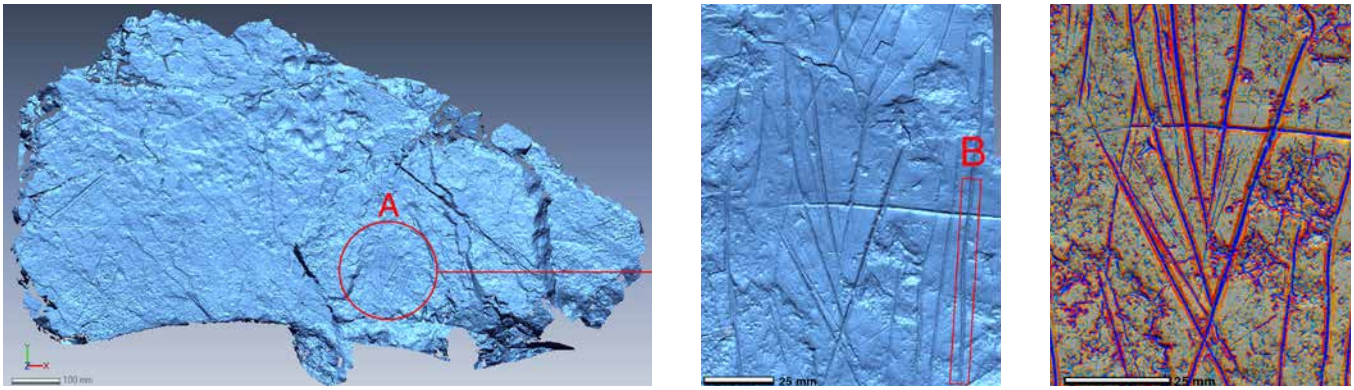


Figure CS4.2
A 3D model of the engraved block, showing the study areas A (left) and detail B (centre), and semi-automatic curvature analysis of A (right)
Courtesy of Vera Moitinho de Almeida

grooves and their subsequent morphological characterisation, (2) to proceed with the analysis and interpretation of the grooves on a quantitative and objective basis and (3) for documentation, archiving, monitoring, management and preservation purposes.

What problems were encountered?

There were logistical (location, distribution and ambient lighting conditions) and technical (engraving types and hardware/software issues) to overcome. In such a delicate archaeological environment care had to be taken with the scanner's cables and devices. The existing scaffold structure held only the necessary equipment: the measuring system and the laptop. The electricity generator was placed far from the workspace as it caused ground vibration. Fabric curtains were mounted to prevent the entrance of sunlight and darken the scanning area homogeneously; the greater contrast produced more consistent data. To save time, only the 3D data acquisition and pre-alignment stages were undertaken on site, the latter to ensure that there were no missing areas and to assess the general quality of the data. Final alignment, processing and analysis of the data were undertaken in the office. Dealing with the large amounts of data proved to be time consuming and difficult for the computer systems to manage.

The study of the engraving morphology with 3D scanning is primarily dependent on the level of accuracy and resolution of the data. The 450mm FOV proved to be unsuitable for this study. It was unable to capture some strokes, and the inaccuracy of a groove's morphology was evident. The grooves became wider, smoother, shallower and less sharp in such a way that it became almost impossible to distinguish one stroke from another and thus proceed with further relevant geometric analysis. The 150mm FOV captured most of the surface irregularities but still lacked some accuracy. These issues can be a problem when characterising and analysing engraving groove families at certain scales, especially if the differences between some of the stroke morphologies are subtle. On the other hand, the 90mm FOV identified previously unknown carvings and captured the engraved stroke morphology more efficiently and objectively, and with a higher level of detail, which best suited the purpose.

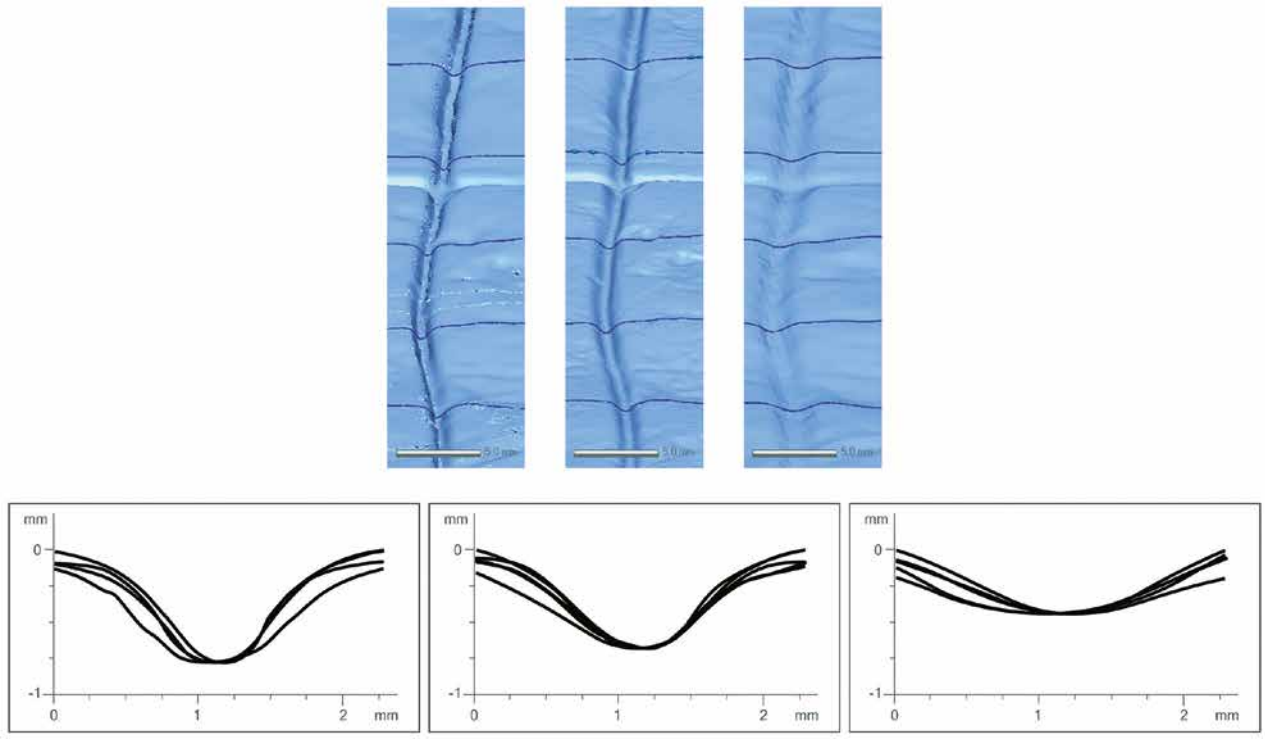


Figure CS4.3
3D Digital models of groove B. Cross-sections (top), overlapped profiles (bottom): 90 (left), 150 (centre) and 450 (right) mm FOV
Courtesy of Vera Moitinho de Almeida

What was the deliverable output?

The normal scan processes, such as decimation, smooth filtering, hole filling and compression, were not carried out in order to avoid concealing or distorting any relevant information, and to maintain the authenticity of the real surface of the engraved block. All the raw data was saved at a repository for potential future reprocessing. Copies of the raw data, as well as processed 3D point clouds and meshes (in STL and PLY formats) acquired with the three different resolutions, were delivered to the University of Cantabria. Interactive virtual light–shadow maps and micro-topographic curvature colour maps for fast visual detection of the engravings were also provided. This case study was developed within the scope of Moitinho de Almeida's PhD research. For a full description and results please consult Moitinho de Almeida et al 2013, and Moitinho de Almeida 2013.

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Case Study 5: The Iron Bridge – 3D modelling

Type: pulse and phase-comparison scanning

Keywords: access, iron, deformation, movement

Introduction

The Iron Bridge is Britain's best-known industrial monument and is situated in Ironbridge Gorge on the River Severn in Shropshire. Built between 1779 and 1781, it is 30m high and the first in the world to use cast iron construction on an industrial scale. It is a scheduled monument and the Bridge, the adjacent settlement of Ironbridge and the Ironbridge Gorge form the UNESCO Ironbridge Gorge World Heritage Site. The bridge is of great significance, being the world's earliest major iron span bridge and the prototype for future iron bridge construction.

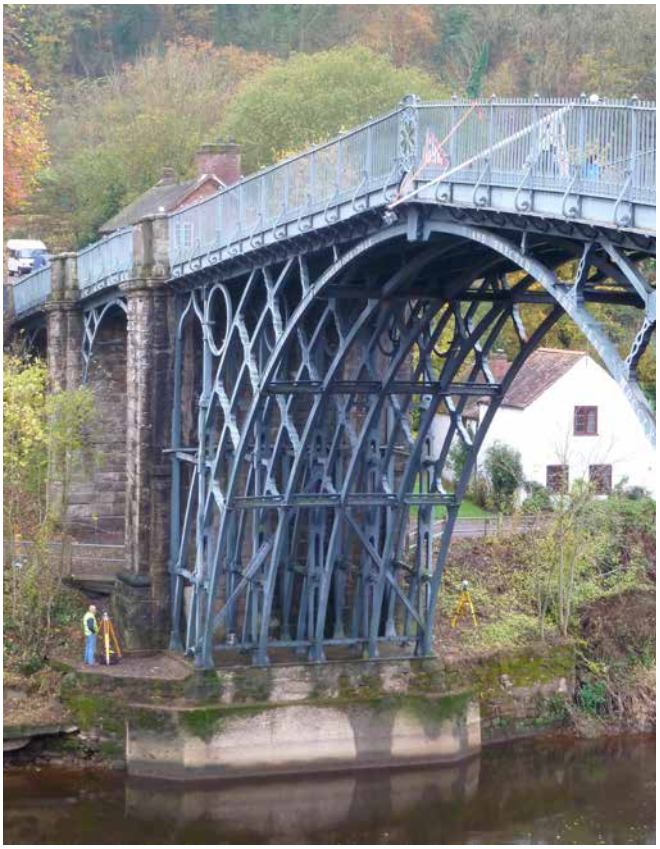


Figure CS5.1
The Iron Bridge: the first bridge to use cast iron construction and now part of a World Heritage Site

Instruments and software

The hardware used included the RIEGL VZ-400 longer range pulse scanner, the FARO Photon shorter range phase-comparison scanner and a Trimble total station. The software used for the processing of the data included RIEGL RiSCAN PRO, FARO SCENE and Pointools Edit.

Why was scanning selected?

APR Services was commissioned to create a highly detailed and accurate laser scan of the structure and the surrounding area for English Heritage. The specification required a 2mm point cloud in colour over every surface of the structure. The point cloud would act as both an archive of the structure and as the basis for the creation of a detailed three-dimensional (3D) model for analysis as part of the bridge conservation plan.

What problems were encountered?

The scanning of the bridge surrounds was undertaken using a RIEGL VZ-400 scanner over two days, by setting up the scanner over control points, with targets similarly set up over control points and in positions that enabled registration of the separate scans. A total of 47 scans was observed.

The bridge itself was scanned over six days using the FARO Photon, which is a shorter range but higher accuracy instrument. Access was a problem and a special hydraulic mast was used to lift the scanner to a variety of heights and locations under the bridge to obtain coverage on all sides of every iron member. A pre-survey site visit and test had shown that this would be successful for the underside on the bridge base positions. It was also found that it was possible to fit the scanner and mast through the bridge railings, extending it out over the sides, in order to scan the underside and the tops of the iron beams. This was necessary as no scaffolding or cherry picker was allowed on the site as the bridge is pedestrian access only. The FARO scanner was triggered remotely by wireless connection from a mobile phone.

Figure CS5.2 (top left)
Scanning using a telescopic mast from above and below the bridge
© APR Services

Figure CS5.3 (top right)
An image of one section of the final point cloud
© APR Services

Figure CS5.4 (bottom)
An image of the final point cloud
© APR Services.

The temperature also had to be monitored at all times during the acquisition of the data. Iron expands and contracts when the temperature varies, so a reference temperature was chosen and the scanning had to be conducted within ±3°C. All scans were georeferenced using a combination of spheres and flat targets to ensure the scans registered accurately. Each scan had to have at least four control targets, which were either coordinated or common to another scan to achieve an acceptable registration. In all, 162 scans were taken in and around the bridge structure. The wind channelling up the valley caused some problems with scanner movement. The wind speed was constantly monitored and every mast scan was checked for any wobble.

Other factors that limited the accuracy of the survey were as follows:

- Bright sunlight would heat up parts of the bridge, causing differential deformation to those areas not exposed

- The bridge was open to the public and could have a variable number of people on the structure at any time. The loading on the bridge could also have caused differential deformation

- Movement as a result of wind and water flow could cause some differential deformation throughout the duration of a scan. Although the scans were registered to fixed control points an amount of 'point cloud registration' was necessary to overcome the effect from loading. Careful manual checking of all scans was carried out to ensure registration was correct throughout

What was the deliverable output?

The many gigabytes of data were cleaned, compiled and averaged to provide the 2mm resolution point cloud required. This was divided into five sections for ease of handling, and the surrounding area was delivered at a density of 10mm. The points included intensity and colour information. All raw and registered point clouds were supplied. Spheron 360˚ HDR photography was also provided for the whole area. A 3D topographic survey was subsequently commissioned in 2016 for the area, which was extracted directly from the point cloud.

Case Study 6: Liverpool Street Station – BIM survey

Type: pulse scanning

Keywords: control, access, data volumes, BIM, client liaison

Introduction

London's Liverpool Street Station is the third busiest railway station in the UK. It was designed and built in the 1870s by Great Eastern Railway Engineer Edward Wilson and the Lucas brothers. The complex and distinctive roof was designed and built by the Fairburn Engineering Company. At the time of building, the roof was spanned by four wrought iron spans and included ten 220m long platforms. Within 10 years of the initial construction, the station was running around 600 trains each day and was at capacity. Work started in 1890 to expand the station eastwards, adding a further eight tracks and associated platforms.

As part of early stage feasibility studies to enhance the station layout, Bridgeway Consulting was commissioned by Network Rail to create a three-dimensional (3D) digital model using building information modelling (BIM), with attention being paid to the historic architectural detail, particularly the areas of the station that are Grade II-listed. The model was to be based largely on 3D laser scan data collected in the field by inhouse surveying teams, which was then to be supplemented by, and cross-checked against, existing asset records.

Instruments and software

A high level of accuracy was key to this project and, prior to undertaking any laser scanning, a robust survey grid was installed using Trimble R6 global navigation satellite system (GNSS) receivers, Leica 1201 1" total stations and Dini digital levels. An external loop was traversed and levelled around the exterior of the station, with an additional secondary loop running through the interior. Laser scanning was undertaken using multiple Leica C10 scanners, referencing the ground control grid. Scan registration and cleaning was carried out using Leica Cyclone, with

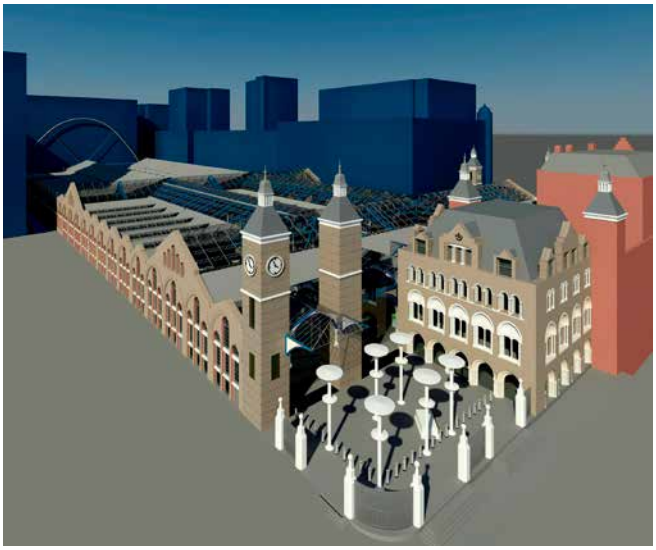


Figure CS6.1 (top)
Liverpool Street Station: a 3D model of the exterior

Figure CS6.2 (centre)
Point cloud and model of the platforms at Liverpool Street Station

Figure CS6.3 (bottom)
Rendered model of the concourse at Liverpool Street Station

point cloud fitting avoided as much as possible to maintain proof of accuracy of the surveys related to the control. All processing and modelling was done using Autodesk ReCap and Revit.

Why was scanning selected?

Initially, the client considered constructing a 3D model from their archive of 29,000 legacy drawings in York, some of which dated back to the original construction of the station in the late 1800s. Relying on these drawings would have imposed a large element of risk when producing a current as-built record, so a full 3D scan was commissioned to supplement the model. Scanning proved to be the obvious choice because of the level of detail required in such a complex station. In all, over 600 terrestrial scans were undertaken to gather accurate data for all the front-of-house areas of the station.

What problems were encountered?

The main challenge was one of access. Liverpool Street is an extremely busy station, with services running up to around 01:30 and starting again at 04:30. This left a very small window in which to work. To mitigate this, meetings with the station management were held to determine what could be achieved while minimising the impact on the public. When access was granted, up to seven teams were mobilised to maximise each opportunity.

The volume of data gathered was also problematic, with the BIM team eager to model their first registered datasets. For this reason the station was broken down into small, manageable areas. While waiting for the first data, the BIM team was able to model the more recent legacy data. This was verified against the registered scans before final issue.

What was the deliverable output?

The post-processing of the vast datasets was a sizable task and it was agreed that splitting the point clouds was essential to reduce the files to a manageable size. Each point cloud was then converted into an Autodesk Revit 2015 native point cloud file format via Autodesk ReCap. Once converted, each point cloud could be linked into Revit in order to reconstruct the station. By linking the separate point clouds into Revit, the process was much more manageable to determine sections and plans through the point cloud. Once these were established the modelling process could begin.

While the point cloud provides an accurate 3D representation, it is still very much dumb data with little embedded information. By using the point cloud and the legacy data, a Revit model could be created that contained data-rich components with built-in parameters to enable additional asset data to be introduced. This embedded data can then provide a wealth of information for renovation, construction, facilities management and the asset life cycle of the station.

The BIM manager attended meetings and workshops with the client to ensure that they were able to access and use the model effectively to conform to their British Standard (BS) 1192 workflows. Additional support was given to help standardise the flow of construction data within future projects.

References

BSI 2007 C*ollaborative Production of Architectural, Engineering and Construction Information: Code of Practice*. BSI Standards Publication BS 1192:2007. London: BSI. https://www.thenbs.com/PublicationIndex/documents/details?Pub=BSI&DocId=285074

Case Study 7: Tregony – survey of a historic walled garden

Type: handheld mobile scanning

Keywords: access, pole, data noise, photogrammetry

Introduction

In October 2016, Cotswold Archaeology was commissioned to undertake a historic building recording and measured survey of a walled garden within the grounds of Roseland Parc Retirement Village, Tregony, Cornwall. The garden was laid out in the early 19th century on a rhomboid plan and formed the kitchen garden of the adjacent Grade II-listed Penlee House, which was built c 1820. The ground slopes down to the east from the house and the central part of this slope is occupied by the walled garden. The garden is thought to date from the construction of the house and was certainly in existence by 1841, when it is recorded on the tithe map.

The walled garden measures c 32.5m by 37.5m in plan and appears to be largely of one build, although with some later additions and repairs. It appears to have fallen out of use in the latter half of the 20th century and early 21st century, with the walls falling into disrepair thereafter. At the time of the measured survey, the wall was in poor condition, with several areas of collapse and removal. Prior to the survey the garden was overgrown, but the interior had largely been cleared when the measured survey was undertaken.

Instruments and software

The measured survey was carried out using a GeoSLAM ZEB-REVO, a handheld laser scanner that allows the user to walk through the survey environment and record points at a rate of 43,200 points per second. In the right conditions, it can capture points at a range of up to 30m with a relative accuracy of 20–30mm. To capture the tops of the walls, the scanner was mounted on a Nodal Ninja extension pole. Overlapping scans were taken of each structural surface to guarantee a high point density, thus ensuring that no voids were left in the dataset. To tie the data to the national grid, control points were surveyed with a Leica Viva GS08 Netrover.

The data was processed using GeoSLAM Desktop, which generated a fully registered point cloud. The scan point cloud was further processed and quality assured in CloudCompare to ensure that all extraneous data was excluded. Following this, a scaled two-dimensional (2D) plan and elevations were produced in Autodesk AutoCAD DWG format.

To complement the laser scanning, a photogrammetric survey of the elevations was also undertaken with a Canon EOS 700D and a 50mm lens. For the purposes of image quality, manual settings were adopted for consistency when adjusting to the lighting conditions on site. The resulting RAW images, once quality checked, were then processed in Agisoft PhotoScan and imported into AutoCAD for scaled elevation drawings.

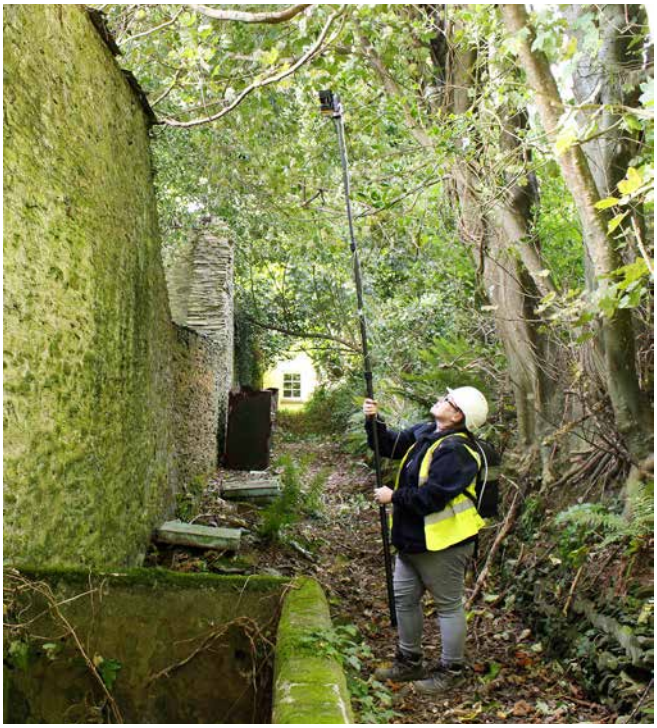
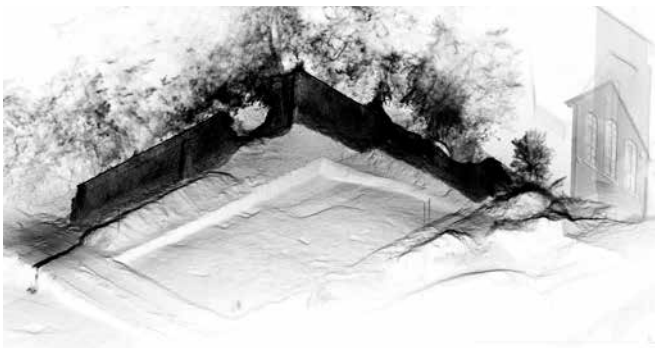
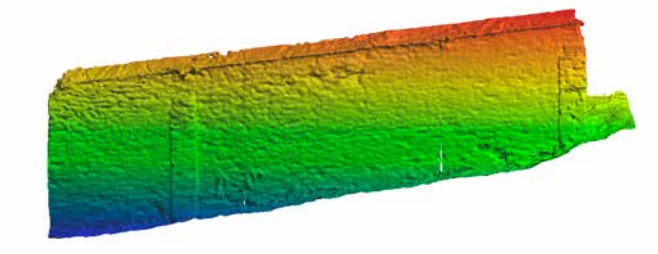


Figure CS7.1
Using a mounted ZEB-REVO on-site





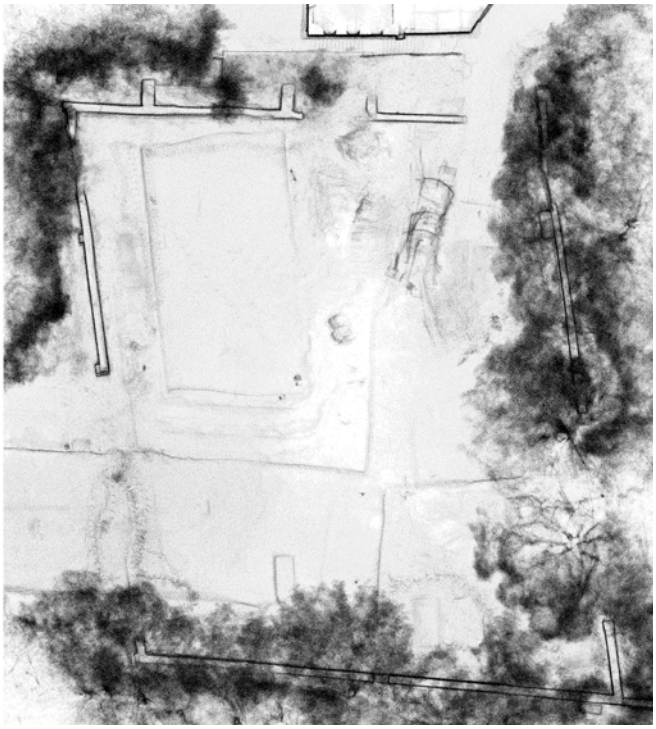


Figure CS7.2 (top)
Scan data showing both the east and south walls, with trees and vegetation to rear. Note the section of collapsed wall at the centre

Figure CS7.3 (centre)
Section of the east elevation (exterior) with coping and buttresses still extant

Figure CS7.4 (bottom)
A plan of the walled garden constructed from scan data

Why was scanning selected?

Because of both the height and line-of-sight of the walls, laser scanning was considered to be the most effective method of data capture as the information had to be gathered in a limited time. Choosing the type of laser scanner to use had to take the environment into account. The vegetation overgrowth was largely cleared from the interior immediately prior to the survey (under archaeological supervision) but several mature trees and dense overgrowth were still present close to the exterior elevations. This severely limited access in some areas so, because of this, the ZEB-REVO laser scanner was chosen as it not only enabled rapid, accurate data capture but also gave the survey team the freedom to move around without constraints. Mounting the ZEB-REVO on an extension pole enabled the team to capture the tops of the walls, which was important where coping was still evident.

What problems were encountered?

Because of the site conditions, the ZEB-REVO produced noisy data that required a significant amount of editing. There was also moving machinery on site that caused some errors. Problems with manoeuvring the ZEB-REVO in tight spaces were also encountered. In some areas of the site access was limited to less than 1m stand -off, which resulted in some errors, but all problems were resolved during the processing stage.

What was the deliverable output?

Using the ZEB-REVO data, several scaled elevation drawings were produced of both the interior and exterior faces. Using AutoCAD 2015, a scaled plan of the walled garden was also produced. The elevation drawings were further enhanced by the photogrammetric survey, which illustrated stone-by-stone detail of some selected elevations.

Case Study 8: Uphill Manor – combining terrestrial laser scan and aerial SfM point cloud data

Type: phase-comparison scanning

Keywords: access, SUA, data integration, accuracy, SfM, photogrammetry

Introduction

The proliferation of terrestrial laser scanners in the as-built survey industry has allowed survey companies to generate vast amounts of accurate, reliable point cloud measurement data quickly and safely, allowing the production of high-quality two-dimensional (2D) measured survey drawings. However, there are some locations where it can be difficult or impossible for terrestrial-based laser scanning to acquire data, such as areas that have restricted or unsafe access. To overcome these difficulties, Greenhatch Group decided to employ structure from motion (SfM) photogrammetry techniques utilising a camera mounted on a small unmanned aircraft (SUA) to work alongside terrestrial laser scanning.

For this project, Greenhatch Group was asked to undertake a full measured building survey of the Grade II*-listed Uphill Manor, Weston-super-Mare, Somerset, which had recently been devastated by fire, leaving large areas of the building damaged and inaccessible. Built in 1805 and previously known as Uphill Castle, Uphill Manor is one of the most historic buildings in the area and served as a hotel prior to the fire. The required output for the survey was a comprehensive set of 2D floor plans, elevations and sections, with additional outputs of aerial images and a three-dimensional (3D) mesh model derived from the SfM photogrammetry.

Instruments and software

The on-site terrestrial survey work was undertaken using Z+F 5010c and FARO Focus3D X 330 phase-comparison scanners, controlled with a Leica TS16i total station and georeferenced with a Leica GS10 RTK global navigation satellite system (GNSS). All scan locations were tied in to the control network using a minimum of four black and white chequerboard targets, with the centre points coordinated by the total station. Aerial imagery was captured using a DJI Phantom 3 Professional SUA carrying a 12MP camera and recording was in Adobe RAW format.

Terrestrial scan data was controlled through McCarthy Taylor Systems LSS survey software and processed with Leica Cyclone in a well-

Figure CS8.1 (left)
Uphill Manor: an aerial image showing the fire damage

Figure CS8.2 (right)
Mesh model using SfM photogrammetry

Figure CS8.3 (top)
SUA point cloud derived from SfM photogrammetry

Figure CS8.4 (bottom)
2D elevations from the laser scan data

tested and accurate workflow. Point clouds were created from the aerial imagery using the SfM photogrammetry software Agisoft PhotoScan Professional and also imported into Cyclone.

To ensure accuracy and coordination of the terrestrial and aerial point clouds, black and white chequerboard and auto-recognition targets were included in the aerial images, with their centre points again recorded by total station. Additional common points were selected and coordinated in both the terrestrial and aerial point clouds for high-level areas where physical targeting was not possible.

Why was scanning selected?

The Greenhatch Group has developed robust, reliable and repeatable workflows, and clients have confidence that this methodology provides accurate results that can be forensically examined for error. For this reason, survey-controlled laser scanning remains the bedrock of the group's work. However, terrestrial scanning has limitations, particularly regarding lines of sight and safe access. For this project, it would have been possible to utilise a hydraulic or scaffolding platform for the high-level work, but this would have added another level of logistics and potential survey errors. The use of a lightweight and low-cost SUA allowed access to the dangerous, burnt portions of the building with little risk to either staff or building structure. Carefully controlled SfM photogrammetry provided large amounts of additional 3D data, while direct comparison and registration to terrestrial scan data provided confidence in the quality of the information.

What problems were encountered?

Three principal problems were encountered with the production and integration of SUA point clouds with the terrestrial scans. The first was confidence in the collection of the right imagery and data. This can only be mitigated through experience or the collection of far more data than is required, with implications for processing times and data storage. The second was confidence in the accuracy of the data. SfM software tends to be more 'black box' in operation than survey companies and clients may be used to, and much more office time than normal was required to be certain that the final point clouds met quality standards. Finally, the visual integration of the aerial and terrestrial point clouds required forethought. SfM point clouds generally contain red, green, blue (RGB) colour but do not have an intensity value, while terrestrial scan point clouds are often captured with intensity only and no RGB colour. To integrate the two point clouds all external scan data was captured with RGB colour, necessitating additional site time.

The successful integration of SUA and terrestrial survey data for the challenging Uphill Manor survey demonstrated the potential of this workflow for similar future projects.

What was the deliverable output?

The final delivered output was full 2D floor plans, elevations and sections of the building, carried out to a high detail level both internally and externally. Within the issued data, drawing sheets were set up for each floor and roof plan, along with elevations and typical sections in DWG file format. These were then exported as PDFs to be viewed easily by anyone. In addition to the 2D outputs, a 3D textured model was produced in OBJ format, along with various aerial images of the site in JPEG format.

Case Study 9: Belsay Castle – laser scan survey

Type: pulse, phase-comparison and handheld mobile scanning

Keywords: access, building complexity, data noise, data processing, illumination

Figure CS9.1 (top)
Belsay Castle

Figure CS9.2 (bottom)
The ZEB-REVO in action

Introduction

Belsay Hall, Castle and Gardens, Northumberland, comprise an English Heritage site 14miles northwest of Newcastle. The site includes an early 19th century mansion in the Greek-Revival style (the Hall) and the medieval tower (the Castle) that preceded it. They are set in 8ha of grounds incorporating a Sicilian-inspired quarry garden. In the early 17th century, a substantial new house was added to the west of the tower, possibly replacing and adjoining other medieval structures, which was itself remodelled to respond to the new building. Following completion of the Greek-Revival mansion, the medieval tower and 17th century house were gradually abandoned and are now conserved in the partially ruined condition in which they came into the care of the state. As part of an English Heritage project to improve the interpretation and thus the visitor experience in the Castle area of the site, the Historic England Geospatial Imaging Team undertook laser scanning of the whole of the medieval tower.

Instruments and software

The castle's tower is a complex of small and large rooms connected by only one spiral staircase and narrow passages. This presented a challenge for static laser scanning because of the number of scan stations required and the difficulty of providing sufficient control.

For the inside of the tower, a FARO Focus3D scanner was used. Its small size and weight meant it was easy to move and set up in confined areas. It was also mounted on an extending tripod to acquire scans in the double-height rooms. At the time of the survey, the site was open to the public so it was not possible to capture much of the spiral staircase. The exterior of the tower was scanned from the ground using the longer range Leica P40. Control in the form of spheres, hemispheres and black and white targets was surveyed using a total station in order to link clusters and to unify the interior and exterior scans. It was also necessary to link a number of scans using cloud-to-cloud registration. The whole point cloud was georeferenced to the national grid by global navigation satellite system (GNSS) observation from two of the traverse stations.

The FARO scans were registered using FARO SCENE while Leica Cyclone was used for the P40 data. The scans were imported into Autodesk ReCap to facilitate viewing by non-specialist users and for potential use in a three-dimensional (3D) modelling environment. Although the plans could have been drawn from this data, the scans were also converted into POD files for use with, the now legacy, Pointools plug-in for Autodesk AutoCAD, as this had more functionality for producing and adjusting the required data slices.

Why was scanning selected?

Laser scanning was chosen as the most efficient way to record the tower internally and externally. A previous survey had been carried in the 1980s using theodolite and hand measurement. To repeat this would have required several weeks on site and accuracy for the more inaccessible areas would have been compromised. The range of scanners available to the Geospatial Imaging Team meant that most of the building could be measured. Laser scanning also allows the lengthy drawing process to be carried out in the office although, being remote from the subject, problems with interpretation can arise.

What problems were encountered?

The completed point cloud covered all the principal rooms but there were some significant gaps, including small side rooms and most of the spiral stair. The team had, however, recently acquired a ZEB-REVO handheld scanner, so this provided an ideal opportunity to test it. The ZEB-REVO consists of a two-dimensional (2D) line scanner mounted on a motorised drive. The rotation of the scanner head provides the third dimension as the user walks around the area of interest. There is also an inertial measurement unit (IMU), which records the motion of the scanner. This, combined with the application of a simultaneous localisation and mapping (SLAM) algorithm in the processing phase, results in a 3D point cloud with a stated range noise of ±30mm. The maximum range in optimal conditions is 30m, although the user manual recommends 15–20m.

The SLAM algorithm relies on plenty of overlap with easily identifiable features in the point cloud. To maintain accuracy it is also necessary to close the loop. As a minimum this means starting and finishing in the same place, but it also helps to have extra loops within the one scanning session. To achieve optimal scans requires careful planning of the route and attention to what is being scanned. The scanner has a very basic user interface and it is not until the data is processed that the results are visible. A route was devised to encompass all the areas missing from the static scans. The results of this scan were mixed, in that all the data on the way up seemed consistent and likewise on the way down. However, there were two versions of the spiral staircase with an obvious offset. This was probably because of the narrow doorway to the roof of the tower, which made it difficult to maintain a suitable overlap. One tip is to enter and exit backwards so that the scanner can still see the detail in the room you are leaving, but this would not have been a particularly safe way to proceed on a spiral staircase. In later versions of the software (3.1.1 onwards), it is possible to adjust the parameters of the SLAM algorithm, and this did result in a better alignment.

The ZEB-REVO is optionally supplied with a GoPro camera to collect video along the route and thus provide more contextual information. At the time of writing (May 2017) a version of the software that will allow colourising of the point cloud is in development. This should be a definite advantage because, as the point clouds have no intensity values, they can be quite difficult to interpret. For the indoor scans it was necessary to use an LED light panel to provide enough illumination for the camera. A second surveyor had to walk behind the scanner holding the light panel and, while manoeuvring in tight spaces, appeared in some of the scans. A better solution would be to use a light mounted on the scanner.

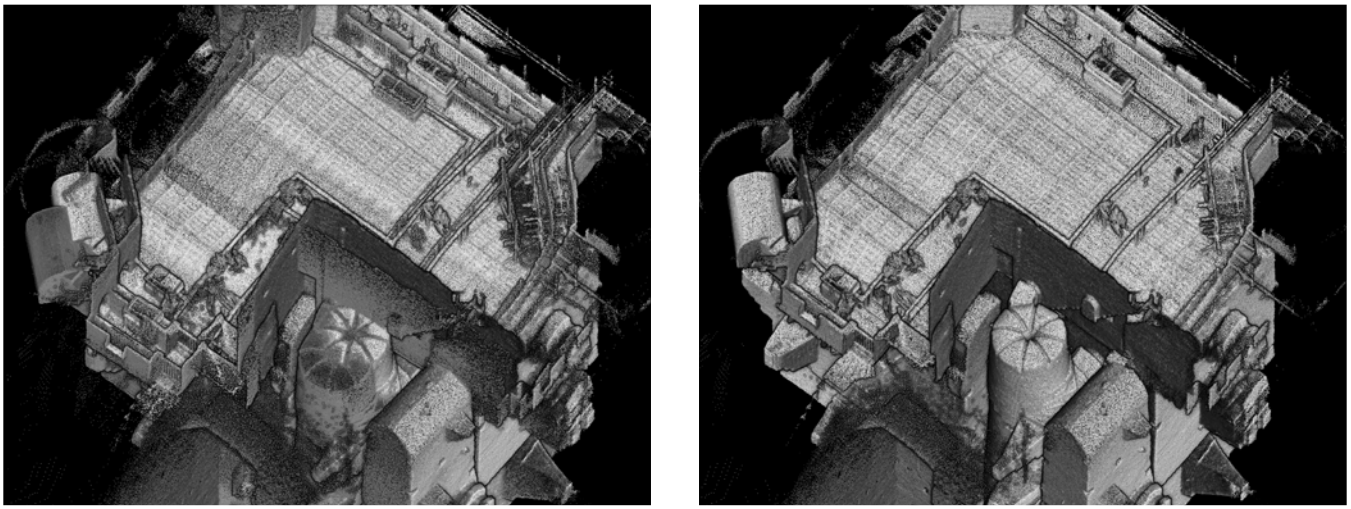


Figure CS9.3
Scan data before and after offline processing to correct the real-time registration problems

What was the deliverable output?

The data from the ZEB-REVO was used to help complete the plans of the tower that had mostly been generated from the static laser scan data. The noise was in the order of 30mm, which meant that some of the detail of the mouldings was not discernible. It was, however, possible to use the point clouds to reference scanned images of the previous hand-measured survey to enable completion of this detail. The noise in the ZEB-REVO point clouds probably means they are not suitable for 1:50 scale plans but will be usable for smaller scale plans for interpretation (eg in guide books), facilities management purposes or circumstances in which the use of a static scanner is not possible. The scans will be merged with those from the static scanners to provide an overall point cloud that could be used as the basis for a 3D model.

Case Study 10: Navajo National Monument – laser scanning and tactile 3D model

Type: pulse and phase-comparison scanning

Keywords: access, logistics, hazards, building complexity, modelling, 3D printing, information accessibility

Introduction

The Navajo National Monument is a park consisting of three monuments dating to 1250–1300 AD, all located within the Navajo Nation in northeast Arizona, USA. The sites are protected by the National Park Service (NPS) and two of the sites, Keet Seel and Betatakin, are open to the public during the summer. Keet Seel is a multi-storey prehistoric village consisting of 154 rooms, exhibiting stone masonry, adobe brick and jacal construction. The standing architecture includes living spaces, storage areas, kivas, a courtyard and bedrock areas. The structures are supported by pine posts located throughout the dwelling.

Keet Seel is located in a narrow alcove 14km north of the Monument visitor centre. The final 5km of the access route must be traversed on foot, a moderately arduous hike that ends with a mounted 14m ladder climb to access the site.

To extend the accessibility of information to a broader sector of the visiting public, NPS required a three-dimensional (3D) tactile model of the Keet Seel cliff dwelling village for the visitor centre. In 2015, IIC Technologies was contracted to create a precisely scaled and highly detailed physical model of Keet Seel using terrestrial laser scanning and 3D printing technology.

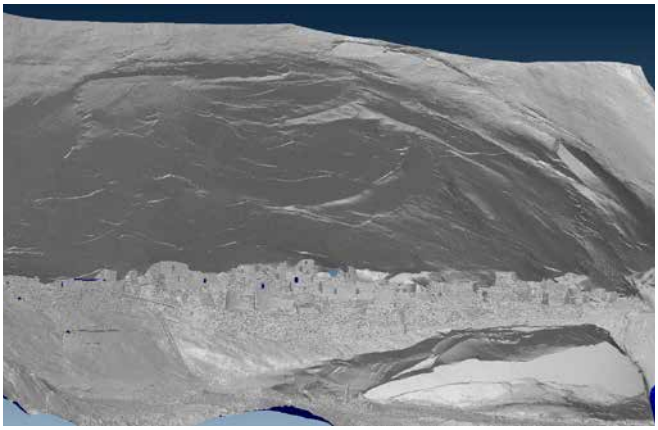
Instruments and software

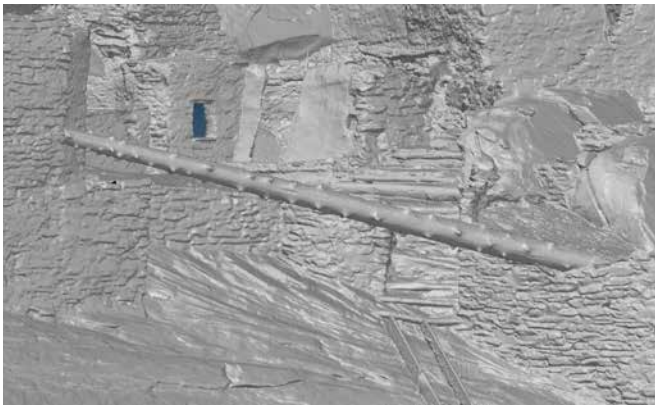
IIC Technologies used two laser scanners, the Leica P40 and FARO X 330. The Leica P40 was selected for surface representation and point density at distances exceeding 100m, which was necessary to capture the rock overhang and canyon wall above the dwelling. The FARO X 330 was selected for its portability and ease of handling in tight spaces and on top of fragile surfaces (roofs of structures).

Figure CS10.1
Keet Seel dwelling

In order to georeference the final point cloud to the appropriate Universal Transverse Mercator coordinate system (UTM Zone 12N), three permanent ground control points were established using a Topcon Hiper Ga global navigation satellite system (GNSS) receiver during two eight hour occupation sessions, and the observations were processed via OPUS Solutions. The high altitude of the site (ellipsoid height greater than 2000m) was taken into account during the processing of control points and a scale factor was applied to the coordinates. To aid display and meshing of the point cloud, the final coordinates were truncated to four digits. The established baseline coordinates were distributed to temporary markers spread throughout the site using a Topcon GPT 3005LW total station. Site layout (large height differences and obstructions) made traversing impossible. Therefore, all visible control points were observed from every ground marker. The processing was carried out with MicroSurvey STAR*NET 3D survey network adjustment.

Scans from both laser scanners were imported to Leica Cyclone for registration. Processing was carried out by dividing the scans into five groups (clusters). Each cluster represented scans collected during one day of survey. Registration was mainly based on artificial targets, fixed





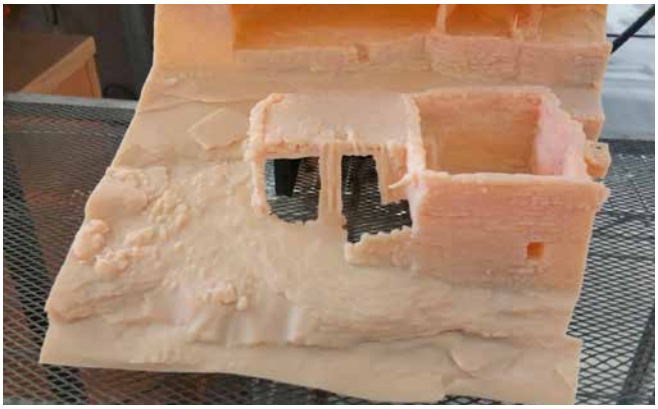


Figure CS10.2 (top left)
Access ladder to the site
© IIC Technologies

Figure CS10.3 (top right)
Mesh model of the dwelling with the overhang
© IIC Technologies

Figure CS10.4 (bottom left)
Close up of the 3D mesh model
© IIC Technologies

Figure CS10.5 (bottom right)
Test 3D print of part of the model
© IIC Technologies

checkerboards, moveable spheres and high definition targets. On a few occasions cloud-to-cloud procedures were necessary to complete the registration. Once cluster registration was complete, final registration to the surveyed control points was carried out. The mean errors for the cluster registration and georeferencing were <3mm and <6mm, respectively.

Each scan was cleaned and clipped to its area of interest using Bentley Pointools. The process minimises noise, significantly reduces imperfections in the registration and removes inconsistency in intensity values caused by range and lighting differences. Preprocessed point clouds were imported to Geomagic Wrap for meshing. Because of the size of the dataset at 7.5mm resolution, the process was carried out in 10 million-point batches. Once all parts of the model were complete, final merging and cleaning was carried out on a watertight surface.

Why was scanning selected?

Scanning was selected for the project as the quickest and most accurate way of collecting data. Limited access because of the site setting and fragility of structures made utilisation of other survey techniques delivering similar data, such as structure from motion (SfM), unfeasible.

What problems were encountered?

Site location meant that the delivery of equipment and supplies could only be carried out on foot. It took three days and several trips to the

site by a team of eight before data capture could commence. Once the survey started, daily hikes were necessary to deliver charged batteries.

The site setting and fragility of the structures made access to some parts of the dwelling difficult or impossible. All moveable targets had to be collected at the end of each survey day because of the presence of wildlife at the site. Appropriate placement of reference targets presented difficulties in some of the locations because of the tight spaces and small openings leading into the structures. Problems with levelling the scanner were encountered in some of the locations that led to inaccuracies in inclinometer readings.

All of the above had a direct impact on data processing. Data had to be processed in daily clusters and some of the scans had to be registered using the cloud-to-cloud technique, and inclinometer readings had to be disabled for registration. The site also presented some unique health and safety hazards. Some parts of the site were marked as inaccessible because of the risk of collapse and fall. Interiors of the structures could only be accessed by staff wearing gloves and face masks because of the potential presence of Hantavirus, which had been recorded previously in similar settings. The IIC team worked well with the NPS to overcome these challenges.

What was the deliverable output?

IIC Technologies delivered the following:

- raw point clouds
- registered and cleaned point clouds in E57 format
- reports covering processing of GNSS data, network adjustment and scan registration
- control point and witness diagrams, and detailed point descriptions
- 3D mesh based on a 7.5mm point cloud in rectangular sections not exceeding 20 million triangles in OBJ format
- 3D watertight mesh for 3D printing at 1:50 scale maintaining the original resolution in STL format
- a robust, tactile model at 1:50 scale for display at the visitor centre, with a removable top part to aid interaction by visually impaired visitors

Case Study 11: Oxford – BIM survey for heritage

Type: pulse and handheld mobile scanning

Keywords: access, topographic survey, level of detail, BIM

Introduction

MK Surveys was commissioned to survey accurately and produce a detailed three-dimensional (3D) model and building information modelling (BIM) of 1 Cornmarket Street and 1–5 High Street, Oxford, Oxfordshire.

Instruments and software

A Leica P40 was used to capture the front facades and the complex roof arrangement, with a handheld ZEB-REVO mobile scanner utilised to record all the internal areas swiftly. The 3D data was compiled into one dataset within Leica Cyclone software using common scan targets. These were also observed using a total station to reference back to the site grid. Check measurements were recorded on site with handheld laser devices and total station observations, to ensure that the simultaneous localisation and mapping (SLAM) technology used by the ZEB-REVO had successfully computed the trajectory and compiled the scan data accurately. All 3D laser scan data was recorded and registered to within the specified tolerances, with the check measurements being within 20mm of the mobile scan data over an entire floor.

A Leica TS15 was also used to record 3D topographical detail of the adjacent roads and footpaths. This topographical survey was processed within the Atlas SCC survey software and delivered to the client as two-dimensional (2D) and 3D AutoCAD files, with the 3D information also used in Autodesk Revit to generate a digital terrain model (DTM) to be added to the final 3D deliverable.

Figure CS11.1
Rendered model of buildings in Oxford

Why was scanning selected?

The cluster of ornate Grade II-listed buildings was occupied by a bank at the time of the measured survey, making access particularly difficult and, therefore, rapid measurement techniques needed to be used. 3D laser scanning was employed in order to record the required survey data quickly while ensuring the complex internal layout, varying floor and ceiling levels and distorted walls were measured accurately to aid the team of 3D technicians to model to the specified tolerance. All required features were captured rapidly on site with minimal disruption to the tenant.

What problems were encountered?

Prior to capturing data with the handheld mobile scanner, a well-planned route was necessary and the surveyor was required to operate at quiet times throughout the day to minimise the effect that too many moving objects would have on the SLAM algorithms. The compiled 3D dataset was inserted into Revit and manipulated at each level of the building to build up the 3D model. Because of the level of detail on the front façade, an agreement with the client was reached to allow simplified modelling of particularly ornate carvings, for example. Problems were encountered when trying to model the distorted walls and uneven planar surfaces such as the floors and ceilings. However, skilled staff were able to apply expert modelling techniques. With patience these problems were overcome and the specification of 'all features to be modelled to within 50mm of the recorded laser scan data' was observed.

What was the deliverable output?

The final deliverable, a 3D Revit model of the building and adjacent roads and footpaths, was successfully completed on budget and prior to the deadline. It is possible to model detailed, complex structures within modelling software but there must be an understanding between stakeholders of the required level of detail and achievable modelling tolerances while always considering timescales and associated costs. Figure CS11.1 illustrates the level of detail agreed with the client.

Case Study 12: Leicester Cathedral – scanning the interior

Type: pulse scanning

Keywords: access, disruption, hazards, level of detail, BIM

Introduction

Leicester St Martin's Church, Leicester, was originally constructed by the Normans before being rebuilt in the 13th and 15th centuries. The Victorians instigated a restoration in 1860 and this work included the construction of a new 67m spire. In the 1920s, when the Diocese of Leicester was reestablished, the church was hallowed as Leicester Cathedral.

In 2012 the mortal remains of King Richard III were discovered beneath a nearby council car park, at the site of the Grey Friars. Planning for the reinternment of the king in Leicester Cathedral began, with the architectural firm van Heyningen and Haward commissioned to design a tomb and reorder the cathedral to take account of the resulting increases in visitor numbers. In order to facilitate this significant undertaking, Plowman Craven was commissioned by the architects to provide a full three-dimensional (3D) scan of the interior of the building to include all structural features and the locations of all existing fixtures, monuments, intricate plaques and tombstones. To help with the planning for the permanent siting of the tomb, particular attention was paid to the thickness of the floor slabs and a service tunnel that runs beneath the main floor.

Figure CS12.1
Leicester Cathedral: a model of the exterior
© Plowman Craven

Following the success of the initial work, Plowman Craven returned in September 2016 to laser scan the remaining internal areas that were outside the scope of the first phase. These areas included the bellringing chamber, the bell chamber and the spire. The external elevations and the surrounding landscape were also captured. Interactive photography was taken and the existing Autodesk Revit model updated to cover the whole cathedral.

Instruments and software

Given the range of practical challenges facing the surveying team on this project, the decision was made to use a Leica P40 laser scanner. The key considerations were the range, quality and accuracy that could be achieved. Additionally, the presence of a survey-grade, dual-axis compensator allowed real-time compensation of the data. It was also perfect for a situation where the geometry of the site required an even spread of control points or where there was limited coverage for cloud-to-cloud registration. The feature that turned off the scanner fans was used in areas where the presence of asbestos had been identified.

For each of the scanner setups, high dynamic range (HDR) 360° panoramic photography was taken to support the work of the team of Revit modellers, providing them with a better understanding of the complete environment when creating and updating the model. In order to register the scan data, Leica Cyclone software was used and the existing datasets formed the basis for the cloud-to-cloud registration of the new scans.

Why was laser scanning selected?

Laser scanning was used because of the speed, accuracy and ability to cover comprehensively the many highly complex internal and external surfaces of the cathedral. Capturing more than a million points per second to an accuracy of 3mm, laser scanning enabled the delivery of a point-in-time archive for heritage recording and reinstatement. In this case, safety and accessibility were also important factors, with laser scanning being the obvious choice both for collecting the data and providing the most complex survey information for building information modelling (BIM) and 3D models.

What problems were encountered?

Throughout the process, the watchword for the survey team was 'disruption'. With the cathedral being in continuous use throughout the period of the project, the scanning had to be conducted without disturbing daily activities. A plan was devised that enabled operation in certain areas at certain times in order to minimise disturbance. There was also the wider issue of sensitivity and confidentiality, given the enormous global interest in the internment of King Richard.

The return visit to survey the remaining internal areas presented a number of challenges, not least the physical characteristics of the cathedral. Confined spaces were commonplace while the geometry of the site (including narrow linear structures such as the spire) made it more difficult to meet the required survey accuracy. Fortunately, a combination of the expertise of the survey team and the versatility of the P40 scanner meant that an accuracy of 3mm was maintained.

The presence of asbestos was another unexpected element, necessitating a complete health and safety plan that included personal protective equipment (PPE) and respiratory protective equipment (RPE). In confined spaces, the wearing of PPE and RPE while carrying heavy survey equipment was extremely challenging for the survey teams.

Figure CS12.2
Scanning in a confined tunnel space
© Plowman Craven

What was the deliverable output?

The client was provided with a complete database of point cloud information that was then used to create a 3D parametric model in Revit. Internal details were modelled to level of detail 2 with level of information (LOI) 200, while external details were modelled to an increased level of detail 3 with LOI 300. These levels of detail were selected to enable future design work to take place. The building elevations, visible roof slopes and surrounding landscape were modelled to a lower level of detail for 3D contextual information. The point cloud database provided by Plowman Craven now sits as a complete archive record that can be accessed at any time throughout the project life cycle or for future proposals.

Figure CS12.3
A model of the interior
© Plowman Craven

Case Study 13: The Roundhouse – reality capture survey

Type: pulse and phase-comparison scanning

Keywords: access, structural problems, sections, data viewing

Introduction

Originally constructed as a mineral and coal wharf, the Roundhouse was strategically placed in the centre of Birmingham to take advantage of the canal to the south and the former London & North Western Railway to the north. The canal network comprised 35miles of waterways and formed the commercial backbone of Victorian Birmingham. It allowed coal and raw materials to be shipped into the city's thriving factories and manufactured goods to be exported across the country.

Materials were stored in the Roundhouse in the large brick barrel-vaulted chambers facing the canal. The central largest arch allowed horse and carriage access from the rear to the secure internal courtyard, where evidence remains of stables for up to 200 horses. Much remains untouched, making the Roundhouse a leading example of Birmingham's rich industrial heritage, as indicated by its Grade II* listing.

Now vacant, the building is owned by the Canal & River Trust who, alongside the National Trust, hope to restore the building to its former glory after being placed on the Heritage at Risk Register. The Heritage Lottery Fund has awarded an initial £225,000 development grant, which will be used to plan for a larger £2.9 million scheme that will see the full restoration of this unusual building. The building will be transformed into a base from which to explore the canal network, including a cycle hire and repair workshop.

Figure CS13.1
An aerial view of the scan data of the Roundhouse

Instruments and software

The following instrumentation and software were used on the project:

- Trimble total stations were used to install and observe an accurate closed traverse externally around the building and internally over each level
- The scanning was completed using both a Leica P20 and a Z&F IMAGER® 5010C
- Leica Cyclone 9.1 software was used to register individual scans into a single unified cloud using visual alignment tools
- Autodesk AutoCAD 2016 was used for the drafting

Why was scanning selected?

In order for the project to develop, The Severn Partnership was commissioned by the Canal & River Trust to undertake a three-dimensional (3D) laser scan of the building to ascertain the extent of the bowing walls and the structural issues. Given the extent of the movement within the building, 3D laser scanning was the only methodology that would facilitate an accurate diagnosis of the building's condition. More than 150 static scans were recorded to gain full interior and exterior coverage. The surveyors completed the site work over three shifts, followed by three days of office processing and seven days of drafting.

What problems were encountered?

Inside the building, the curved vaulted roof structure was only accessible via small ceiling hatches. By utilising an extending tripod that reached 3.5m, scans of above the ceilings could be conducted through each hatch. This information was critical to determine the magnitude of the spreading and the condition of the structure. Although point cloud registration can be a complex exercise, the distinct curvature of the building meant that establishing common detail when carrying out visual alignments was much easier.

Figure CS13.2
Scan data of part of the interior courtyard

What was the deliverable output?

The following products were delivered to the client:

- Twenty eight sections strategically placed to allow for in-depth structural analysis. Software packages such as Autodesk Revit do not offer the user much flexibility when recreating complex 3D geometry. In this instance, where the tolerance needed to be as low as possible, a 2D output was the better solution
- A single unified point cloud
- Leica TruView for client viewing of the data

References

Further information can be obtained from the following websites:

https://www.nationaltrust.org.uk/news/lottery-boost-for-famous-birmingham-landmark

http://www.birminghampost.co.uk/business/commercial-property/birmingham-landmark-roundhouse-reborn-11542482

http://www.hidden-spaces.co.uk/roundhouse/

Figure CS13.3
Scan data of the exterior

Case Study 14: Priory House – laser scanning and modelling

Type: phase-comparison scanning

Keywords: access, modelling issues, data viewing, BIM

Introduction

The Grade II-listed Priory House, Dunstable, Bedfordshire, is built on the site of Dunstable Priory's guest house for travellers and incorporates a splendid 13th-century groyne vaulted stone ceiling and original Tudor fireplace. After the dissolution of the monasteries, the building became a private house from 1545. One of the earliest owners was the Crawley family, who used part of the building as an early hospital for the mentally ill. In 1743 the original stone vaulted hall was incorporated into a much larger house with the Georgian facade and internal details seen today.

Upon the recommendation of Tobit Curteis Associates LLP, Freeland Reece Roberts architects acting on behalf of Dunstable Town Council approached Stanburys Ltd to undertake a series of metric surveys on the Priory House and Tea Rooms as part of an ongoing monitoring and refurbishment project. For Stanburys, this involved a topographical survey, building elevations, sections, floor plans, a three-dimensional (3D) model and a means of viewing the survey results in an accessible 3D medium.

Instruments and software

A survey of the topography and an outline of the structure were undertaken using a Leica 1200 total station and a real time kinematic (RTK) global navigation satellite system (GNSS) was employed for referencing the data to the national grid. During this process pre-positioned internal and external scan targets were also observed to facilitate georeferencing of the scan data. A FARO Focus3D laser scanner was then used both

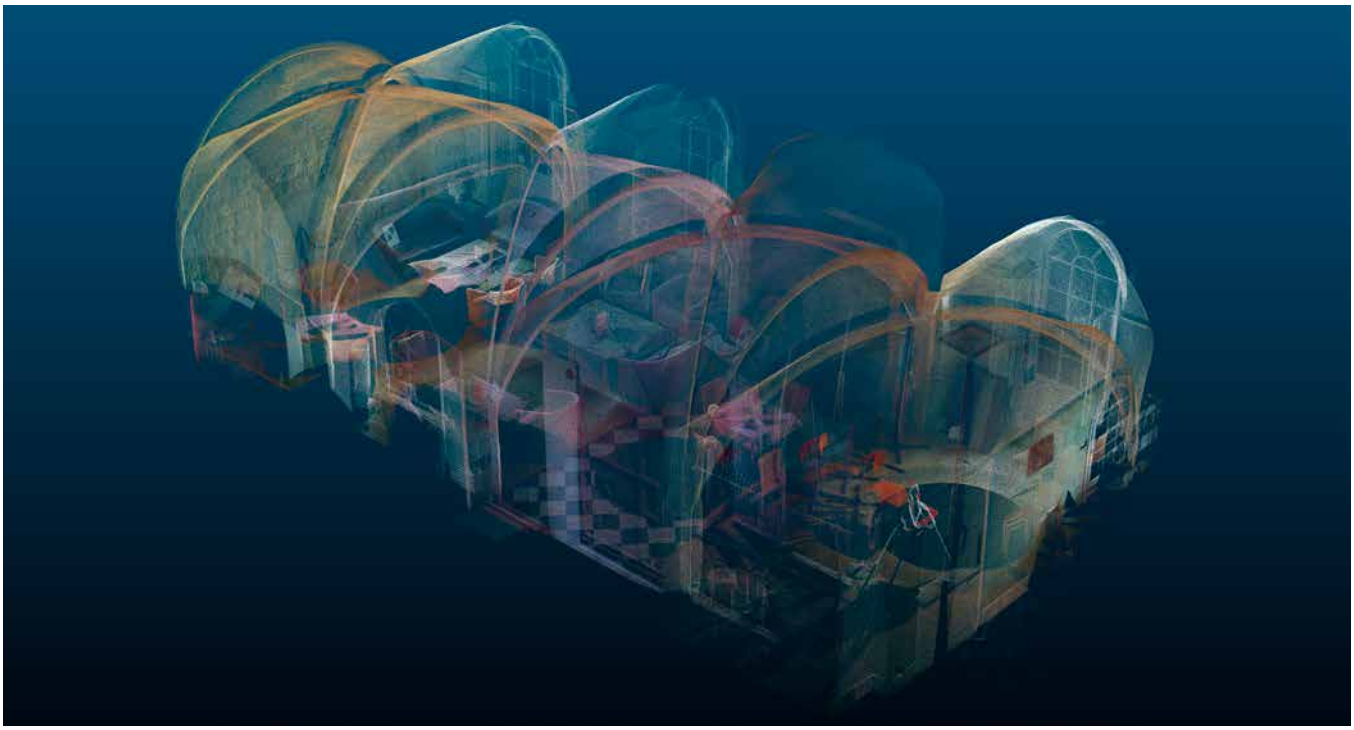


Figure CS14.1
Priory House: colour laser scan data for the vaulted medieval under croft

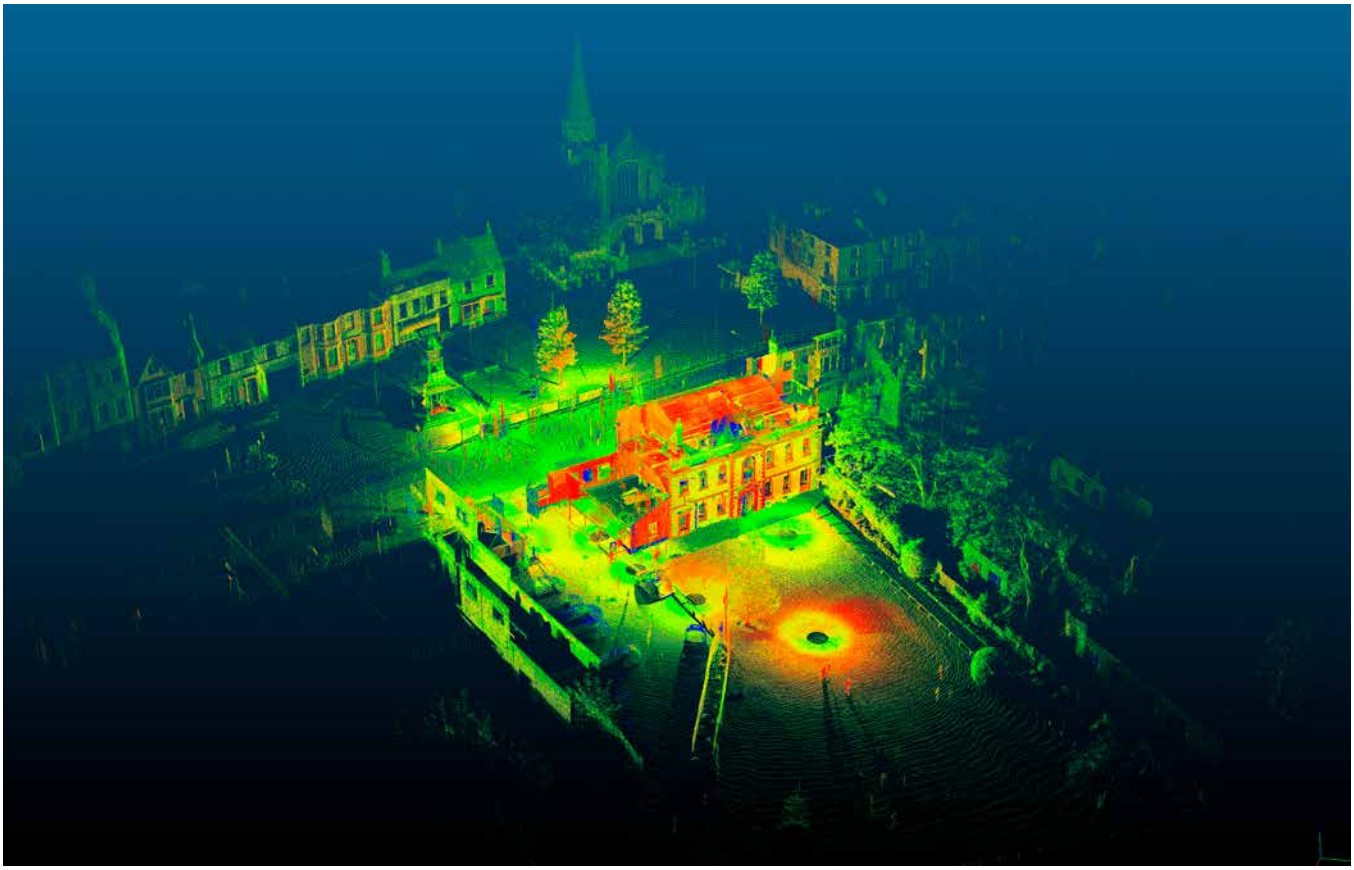


Figure CS14.2
An aerial view of the external laser scan data

externally and internally to capture the structure in its entirety, with 92 scan locations used. Scan positions were linked using chequerboard targets and reference spheres.

Processing and collation of the scan data were undertaken using FARO SCENE, with survey control improving the quality of the registration. Further enhancement of the registration was achieved by using small clusters of no more than 15 scan positions within the main registration file. Once registered the point cloud data was exported in E57 file format and a WebShare (web-based viewing software by FARO) product of the complete scan project was also created. The E57 file was then loaded into Autodesk ReCap, unified and exported in the RCS file format. This was then directly imported into both AutoCAD and Autodesk Revit software. Autodesk 3ds Max was used for some final rendering work. Modelling on the whole was undertaken in Revit using the point cloud as a template, which could be sliced or sectioned to ensure the model was constructed to suitable tolerances.

Why was scanning selected?

Laser scanning was selected because of the speed at which accurate data could be captured in an environment that encounters high volumes of pedestrian traffic and which could not feasibly be closed during the survey. Given the requirement for a 3D model, it was also deemed ideal as it enabled a complete dataset to be collected in one visit. This eliminated the need for costly revisits because of missing data, which can arise with other survey methods. It is also worthy of note that, because of the age and irregular nature of many of the surfaces within the building, laser scanning offered the best means of capturing and recording such surfaces.

Figure CS14.3 (top)
External material render of the Revit model
© Stanburys Ltd

Figure CS14.4 (bottom)
Internal material render of the main reception area
© Stanburys Ltd

What problems were encountered?

No major problems were encountered during data collection, although the fact that the premises were open to pedestrians throughout the survey period meant that additional targets were needed to compensate for any inadvertent disturbance by pedestrians or staff members. Cloud-to-cloud (manual) registration of the scan data could have been used had this occurred, but it was felt that target-based registration offered a superior solution. From a modelling perspective, because of the historic nature of the structure, the lack of squareness of the walls and the irregularity of the surfaces led to various issues with Revit. Additional effort was required to join these more complex elements.

What was the deliverable output?

A WebShare of the entire scan project was supplied to the client as a visual record of the environment within and immediately external to Priory House. This enabled the client to interrogate and annotate the survey data fully, extract measurements, coordinates and levels and export screen shots if required. Scan data was also supplied in E57 file format, which, being an industry standard, should enable future import into most (if not all) laser scan software. As a means of further visualising and viewing the building, an Autodesk Revit model was supplied along with a selection of static and stereoscopic renderings, which were produced in both Revit and 3ds Max and rendered in the web cloud. This model could be further developed for future projects, if required, which might prove useful given that the government is pursuing the use of building information modelling (BIM). BIM is currently mandatory for UK public sector construction projects but it will probably become applicable to all projects in the future. Building elevations, floor plans and sections were also supplied to the architect.

Case Study 15: The Barley Hall Hub – scanning of archaeological artefacts

Type: structured light triangulation scanning

Keywords: artefacts, modelling issues, information access, visitor interaction

Introduction

The Barley Hall Hub is an interactive kiosk allowing visitors to Barley Hall, York, to interact with digital artefacts. This project involved the scanning of 20 archaeological artefacts dating from the 15th century and the creation of an interface based on HTML (a web-programming language), which was installed on a touch-screen kiosk. The type of objects to be digitised varied between pottery, metalwork, bone and leather.

Instruments and software

A DAVID structured light scanner (SLS) was chosen to digitise the objects. It is a competitively priced modular scanning solution, now owned and distributed by Hewlett Packard. Before scanning can commence, the DAVID SLS scanner needs to be calibrated relative to the size of the object to be scanned. This is achieved with a set of calibration boards. The scanner works by projecting a mathematical pattern onto the object and recording the distortion created by the surface using a camera mounted beside the projector. The software then calculates the result and builds a three-dimensional (3D) mesh of the object within the scan area. Only the portion within the scan area is modelled, so multiple scans are required to capture whole objects. The subsequent scan should include an

Figure CS15.1 (top left)
The DAVID SLS setup
© York Archaeological Trust

Figure CS15.2 (top right)
The Barley Hall Hub kiosk in use
© York Archaeological Trust

Figure CS15.3 (bottom left)
Seal matrix and digital wax impression
© York Archaeological Trust

Figure CS15.4 (bottom right)
Embossed leather scabbard (untextured)
© York Archaeological Trust

overlap of the previous scan (for registration) and a simple turntable is used to speed up the process. Typically a scan takes under 20 seconds to complete, and the level of detail (resolution) selected for this project was c 0.2mm. It is also possible to record red, green, blue (RGB) colour information and then align the colour of the object onto the digital mesh using a UV map [two-dimensional texture coordinates projected onto a three dimensional surface].

The registration software that accompanies the scanner is powerful and accurate. Multiple tools allow a quick registration of the 3D scans and fine registration enables the user to build the digital model sequentially scan by scan while checking the accuracy. There is an auto-align function but this does not produce the same accuracy as registering each individual scan in sequence. However, the auto-align function is useful to guide the process of scanning by identifying gaps and areas of the project that may require further scanning. Once the scans are registered the software fuses them together to produce the final output model. The fuse function has options for decimation, smoothing and hole filling.

Why was scanning selected?

Laser scanning was chosen for this project because it offered a precise and cost-effective way of recording the artefacts in the organisation's possession. To capture the form and fine details of the objects fully, a recording technique was required that was capable of sub-millimetre 3D measurement. The DAVID SLS met the requirements for this task and the technology enabled the production of the required 3D mesh models in the same workflow.

What problems were encountered?

Shiny or transparent objects will not scan well unless they have been coated in a fine powder such as chalk. This is not likely to be acceptable in most situations, so the choice of objects to be scanned will always be influenced by the ease of scanning. Some of the bone objects were very reflective and some data voids were experienced. However, these were greatly reduced when the scans were conducted in a dark room. Results are much better if the object is only lit by the scanner's projector during scanning. The RGB colour capture function is fairly low in resolution and does not match the level of detail of the data that the scanner captures. To texture the models accurately, a digital camera was used to capture high-quality images and map those onto the surface of the digital objects in an external 3D modelling package.

What was the deliverable output?

The 20 archaeological artefacts were individually scanned using the DAVID SLS system, producing some pleasing results. The seal matrix model was used to create a digital wax impression as if it were pressed into hot wax, without the need to subject the object to anything other than the scanner's projected light. Using this technique, fragile objects can be examined without any threat of damage. The leather scabbard model was the subject of detail enhancing techniques to help make the embossed design clearer. The digital models of the artefacts could also be shared with fellow practitioners and specialists through email or 3D prints.

A simple HTML-based touch screen interface was designed to enable the objects to be digitally displayed within the Barley Hall visitor attraction. The interface allows visitors to interact with the objects by selecting and rotating them on screen. Further learning is available through the accompanying visual and audio information associated with each object. This project is an excellent example of how digital technology is transforming the visitor experience. Using digital models, access to undisplayed collections is provided and 3D printing technology can create accurate replicas for research and handling collections. The relatively low cost of the DAVID SLS and the speed at which it operates makes this an attractive scanning solution for the digitisation of archaeological objects. More objects are being scanned and made available to the public for this project.

Case Study 16: London – highway mobile mapping

Type: vehicle-based mobile pulse scanning

Keywords: access, traffic issues, survey speed

Introduction

How can a busy highway be surveyed quickly with minimal disturbance to traffic and yet be accurate enough for engineers to use the data for design purposes? Mobile mapping systems combine laser scanning and global navigation satellite system (GNSS) technology and inertial motion sensors into a single unit that is easily mounted onto any road-, rail- or water-borne vehicle. This vehicle-mounted mapping system, as it moves through the landscape, captures laser scan data and high-resolution images simultaneously and the mass of data is then used by surveyors to create accurate computer-aided design (CAD) plans, animations and three-dimensional (3D) models ideal for building information modelling (BIM).

For this project, the client required a full detail topographic survey compliant with Transport for London (TfL) standards, extending to the back of pavements across a busy five-way road junction in the heart of London.

Instruments and software

The equipment employed on the project comprised:

- a Leica Pegasus:Two mobile mapping system
- Trimble 1" total stations, to observe an accurate closed traverse around the site
- Esri ArcGIS software, to adjust multiple passes of mobile lidar data in plan and height with the Leica Map Factory plug-in
- Leica Cyclone software (version 9.1), to clean the point cloud of any moving objects

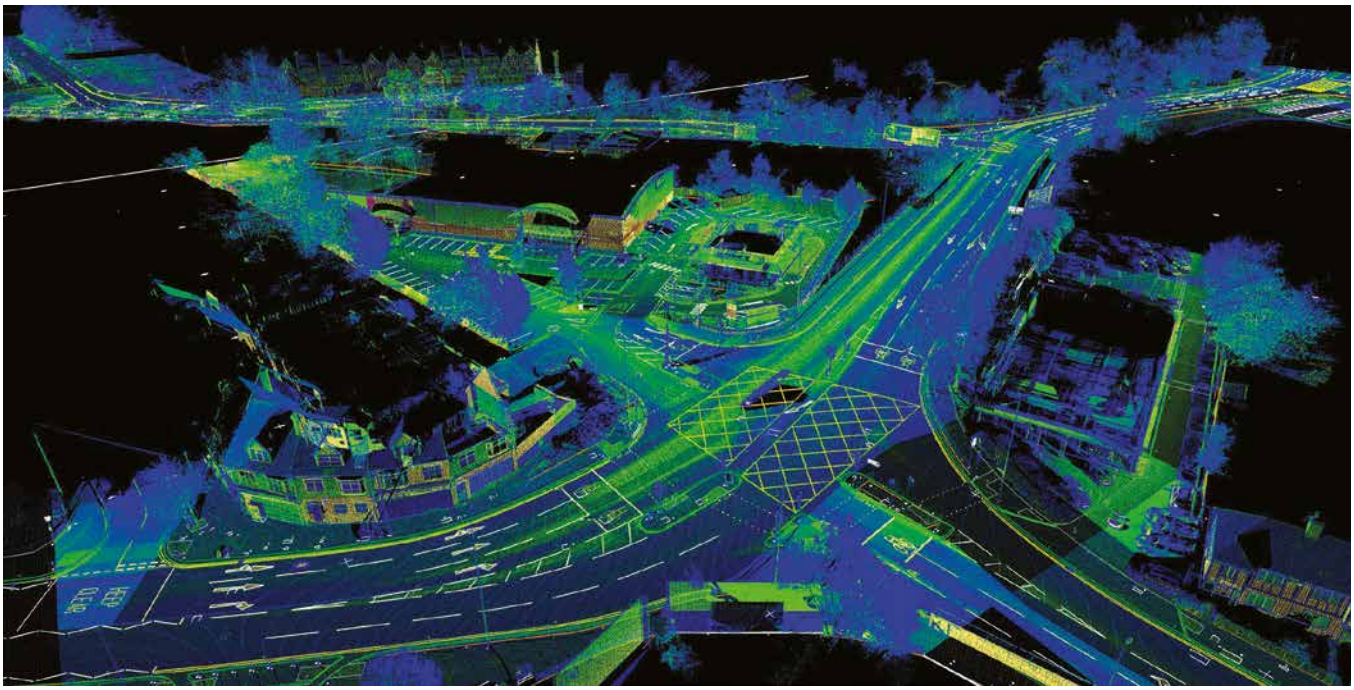


Figure CS16.1
Oblique view of the registered scan data of the road junction

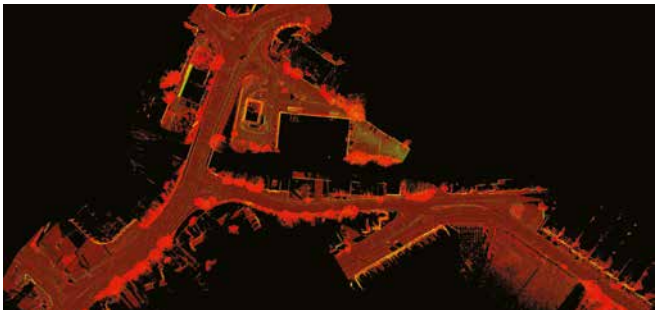


Figure CS16.2 (left)
A vertical view of the registered scan data
© The Severn Partnership

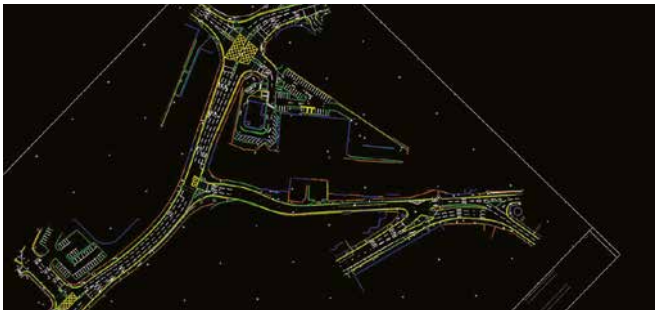


Figure CS16.3 (right)
Topographic plan of the road junction
© The Severn Partnership

Why was scanning selected?

Traditional survey techniques would have required significant traffic management and road closures, with all the work having to be completed at night. This would have resulted in a long lead-in time for planning, with consequent delays for data delivery. Using mobile mapping, Severn Partnership completed the site survey work in a single midweek night shift, avoiding peak traffic hours and any disruption to the public. A robust survey control network was installed and coordinated so that accuracies of ±10mm were maintained throughout the site. Traditional survey methods would have required six team shifts working under traffic management.

The Leica Pegasus:Two was chosen to produce a high-quality survey grade deliverable and it provided the following benefits over traditional survey techniques:

- there was an 80% reduction in site time
- no traffic management was required
- the mass data reduced the risk of missing information
- the point cloud allowed third-party quality control of the extracted topographic information
- the point cloud data could be used as a basis for BIM by the engineers

What problems were encountered?

The busy junction posed significant challenges but the method chosen and the speed of the data collection meant that any potential problems of access, safety and security of personnel and equipment, and disruption to the public, were completely avoided.

What was the deliverable output?

A full set of the registered scan data and a 3D CAD were delivered to the client, along with a full survey report detailing the methodology used and the achieved accuracies.

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6 Glossary

The following glossary explains some of the technical terms and acronyms used in the document:

3D Three dimensional representation using coordinate values relative to the X, Y and Z axes of a Cartesian system

ADS – Archaeology Data Service, an open access digital archive for archaeological research

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

BIM – Building Information Modelling, a collaborative process for the production and management of structured electronic information and illustrating, in digital terms, all the elements that compose a building

CAD – Computer-Aided Design/Drafting, describes graphics software used primarily in engineering and design

Cartesian coordinates Define a position in space using three axes at right angles given by x, y and z coordinates

CIPA The International Committee of Architectural Photogrammetry. The scope of the organisation has widened to cover all heritage documentation. It is a subsidiary committee of ICOMOS, the International Council of Monuments and Sites, and ISPRS, the International Society of Photogrammetry and Remote Sensin

Closed-loop traverse A survey traverse that begins and ends at the same point creating a polygon that can be analysed for error propagation. They are used in the establishment of coordinate networks

Cultural heritage The evidence of human activity (including artefacts, monuments, buildings and sites) that has a cultural value placed on it by society

Data voids or shadows Holes within the point cloud that contain no data because of the type of material being scanned or because the area is obscured from the scanner

DEM – Digital Elevation Model, a digital representation of a surface. Digital Surface Model (DSM) and Digital Terrain Model (DTM) are type of DEM

DSLR Digital single lens reflex camera

DSM – Digital Surface Model, a topographical model of the Earth's surface including terrain cover such as buildings and vegetation

DTM – Digital Terrain Model, a topographical model of the bare earth, also known as a Digital Ground Model (DGM)

E57 A non-proprietary format for point cloud data, developed by the American Society for Testing and Materials. It is a more universal and flexible system than LAS and allows for the inclusion of, for example, image data, gridded data and different coordinate systems

Electromagnetic radiation A general term covering the range of waves in the electromagnetic spectrum. The spectrum includes radio waves, infrared radiation, visible light, ultraviolet radiation and X-rays

Full waveform scanner This type of laser scanner digitises the echo signals (the full waveform) at a high frequency so that the subsequent analysis can retrieve all the information contained in the echo

Geometric accuracy The closeness of a measurement to its true value. The measure of accuracy is normally the root mean square error and gives an estimate of the difference between the actual (or predicted) value and the observed values

Geometric precision The distribution of a set of measurements about the mean value. The measure of precision is the standard deviation and is further defined by the probability of error. For example, if the standard deviation is 5mm then there is a 67% probability that an observation is within 5mm of the mean and a 95% probability that it is within 10mm. It quantifies the variability or repeatability of the instrument

GIS – Geographical information system, a database and analytical software where the information is related to a graphical representation of the surface of the Earth

GNSS – Global Navigation Satellite System, a system that enables surveying or navigation by reference to a number of satellite constellations

GPS – Global Positioning System, a generic term used to describe surveying or navigation by reference to a satellite constellation although it is specifically the name for the satellite constellation operated by the USA. See also GNSS

HDR – High Dynamic Range, an image with a greater range of luminance (the intensity of light emitted by an object) than a normal exposure and is usually a composite of several differently exposed photographs

IMU – Inertial Measurement Unit, a system using accelerometers and gyroscopes to calculate, by dead reckoning, the path of the equipment on which it is mounted

LAS Laser Scanning data format, an ASCII (text) format developed by the American Society of Photogrammetry and Remote Sensing, mainly for aerial lidar

Laser Light amplification by stimulated emission of radiation, an electronic optical device that emits coherent light radiation. The light is collimated to ensure there is little divergence of the beam over long distances

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

Lidar Light detection and ranging, a system that uses laser pulses to measure the distance and reflectivity to an object or surface, normally used to refer to airborne laser scanning but also applied to some ground-based systems

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

Metadata Data that describes other data and facilitates the re-use and archiving of survey datasets

Model Normally preceded by the mode type, eg mesh, geometric or building information and describes a digital 3D representation of a structure, shape or surface

Odometer An instrument for measuring the distance travelled by a wheeled vehicle

Parallax The apparent displacement of an object due to a change in the position of the observer

Peripheral data Additional data collected during the scanning exercise that may be superfluous but may also help the registration process

Photogrammetry The art, science and technology of determining the size, shape and identification of objects by analysing terrestrial or aerial imagery

Point cloud A set of x,y,z coordinates that represents the surface of an object and may include additional information such as intensity or RGB values

Point density The average distance between x,y,z coordinates in a point cloud, sometimes defined as the number of points per square metre especially in airborne laser scanning

Recording The capture of information that describes and documents the physical configuration and condition of the component parts of historic buildings, monuments and sites

Registration The process of transforming separate point clouds and the scan positions into a common coordinate system

Repeatability A statement of the variation of measurement to an object under the same conditions and in a short time. See also Geometric precision

RTK – Real Time Kinematic satellite navigation systems use correction signals to achieve very high accuracy GNSS positioning

Scan orientation The approximate direction in which the scan is pointing if the system does not provide a 360° field of view

Scan origin The origin of the arbitrary coordinate system in which scans are performed. Each scan origin is normally transformed into the site coordinate system during registration

Scan position The location from which scanning is performed. If the system does not perform a full 360° scan, several scans may be taken from the same position but with different orientations. The position can be known directly through placing the scanner over a control point or, as is normally the case, calculated from control in the field of view

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

Segmentation This process divides the point cloud data into consistent or homogeneous units according to range, intensity and colour values

SLAM – Simultaneous Localisation and Mapping, an algorithm developed for handheld mobile laser scanning systems

Specular reflection Highly reflective surfaces produce large variations in the intensity return of a laser pulse and can affect the quality of the data

Surface normal A vector at right angles to a flat surface or to a plane tangential to a curved surface. The normals are calculated in 3D modelling to define the orientation of a surface for shading purposes

Survey control Points of known location that define a coordinate system to which all other measurements can be referenced

System resolution The smallest unit of measurement of a laser scanning system that defines the maximum point density achievable. The resolution actually used will normally be commensurate with the instrument's precision

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

TIN – Triangulated Irregular Network, a vector-based representation of a surface made up of irregularly distributed nodes and lines that are arranged in a network of adjacent triangles. Also known as a triangular mesh

TST – Total Station Theodolite, a survey instrument used to record angles and distances

7 Where to Get Advice

7.1 Charters and guidance

The concept of documentation of cultural heritage was enshrined in the Venice Charter of 1964 (ICOMOS 1964) with the objective of recording all stages of the conservation process, archiving the information in a public institution and making it available for further research.

For those interested in the 3D visualisation of cultural heritage there are two other charters that aim to standardise the digital representation of sites. For all cultural heritage there is the London Charter (Denard 2009).

The London Charter then spawned the Seville Charter in 2011 specifically for visualisation of archaeological heritage (International Forum of Virtual Archaeology 2011).

Overall guidance and a detailed specification for the use of recording techniques are found in Historic England's Metric Survey Specifications for Cultural Heritage (Andrews *et al* 2015).

7.2 Organisations

There are a number of organisations whose members have expertise in or produce standards/guidance for the provision of measured survey of historic sites. They may be able to advise on specifications, training and data archiving, or help locate an appropriate contractor. Examples include the following:

- Historic England Geospatial Imaging Team, 37 Tanner Row, York YO1 6WP, UK

https://historicengland.org.uk/research/methods/terrestrial-remote-sensing/specialist-survey-techniques/

https://historicengland.org.uk/images-books/archive/

- The National Archives, Kew, Richmond, Surrey TW9 4DU, UK

http://www.nationalarchives.gov.uk/

- Heritage Gateway (online)

http://www.heritagegateway.org.uk/gateway/

- Historic Environment Scotland, Longmore House, Salisbury Place, Edinburgh EH9 1SH, UK

https://www.historicenvironment.scot/

https://www.historicenvironment.scot/archives-and-research/archives-and-collections/

- Cadw, Welsh Government, Plas Carew, Unit 5/7 Cefn Coed, Parc Nantgarw, Cardiff CF15 7QQ, UK

http://cadw.gov.wales/?lang=en

- Royal Commission on the Ancient and Historical Monuments of Wales, Fford Penglais, Aberystwyth SY23 3BU, UK

https://rcahmw.gov.uk/discover/historic-wales/

- Remote Sensing and Photogrammetry Society (RSPSoc), Laser Scanning and Lidar Special Interest Group, c/o School of Geography, The University of Nottingham, University Park, Nottingham NG7 2RD, UK

http://www.rspsoc.org.uk/

- Royal Institute of Charted Surveyors (RICS), Geomatics Professional Group, 12 Great George Street, Parliament Square, London SW1P 3AD, UK

http://www.rics.org/uk/about-rics/professional-groups/rics-geomatics-professional-group/

- Chartered Institution of Civil Engineering Surveyors (CICES), Dominion House, Sibson Road, Sale M33 7PP, UK

https://www.cices.org/

- The Survey Association, Northgate Business Centre, 38 Northgate, Newark-on-Trent NG24 1EZ, UK

http://www.tsa-uk.org.uk/

- The Survey School (The Survey Association), Waterworks Road, Worcester WR1 3EZ, UK

http://www.surveyschool.org.uk/

- The Archaeology Data Service (ADS), Department of Archaeology, University of York, King's Manor, Exhibition Square, York YO1 7EP, UK

http://archaeologydataservice.ac.uk/

7.3 Books

The following provide useful insights to metric survey methods in cultural heritage and laser scanning generally:

Andrews, D, Bedford, J and Bryan, P 2015 *Metric Survey Specifications for Cultural Heritage*, 3rd edn. Swindon: Historic England.

https://content.historicengland.org.uk/images-books/publications/metric-survey-specifications-cultural-heritage/metric-survey-specifications-for-cultural-heritage-3rded.pdf/

Antonopoulou, S and Bryan, P 2017 *BIM for Heritage: Developing a Historic Building Information Model*. Swindon: Historic England.

https://historicengland.org.uk/images-books/publications/bim-for-heritage/

Bedford, J and Papworth, H (eds) 2010 *Measured and Drawn: Techniques and Practice for the Metric Survey of Historic Buildings*, 2nd edn. Swindon: Historic England (Out of print).

Bedford, J 2017 *Photogrammetric Applications for Cultural Heritage. Guidance for Good Practice*, Swindon, Historic England.

https://historicengland.org.uk/images-books/publications/photogrammetric-applications-for-cultural-heritage/

Andrews, D, Blake, B, Fradgley, N, Lunnon, S and Roberts, P 2005 *The Presentation of Historic Building Survey in Computer Aided Draughting*. Swindon: Historic England.

https://historicengland.org.uk/images-books/publications/historic-building-survey-in-cad/

Crutchley, S 2010 *The Light Fantastic: Using Airborne Lidar in Archaeological Survey*. Swindon: Historic England.

https://historicengland.org.uk/images-books/publications/light-fantastic/

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

Shan, J and Toth, C (eds) 2009 *Topographic Laser Ranging and Scanning: Principles and Processing.* Boca Raton: CRC Press.

Stylianidis, E and Remondino, F (eds) 2016 *3D Recording, Documentation and Management of Cultural Heritage*. Dunbeath: Whittles Publishing.

Vosselman, G and Maas, H-G (eds) 2010 *Airborne and Terrestrial Laser Scanning*. Boca Raton: CRC Press.

7.4 Journals and conference proceedings

There is no journal dedicated to laser scanning, but many academic journals that publish survey, architecture and cultural heritage articles regularly include papers on the subject. Examples include:

- ISPRS Journal of Photogrammetry and Remote Sensing, Elsevier, Amsterdam
- The Photogrammetric Record, Wiley-Blackwell, Oxford
- Journal of Architectural Conservation, Routledge, Oxford

There is also a range of professional journals that often provide relevant articles, equipment announcements and reviews, including:

- Geomatics World, Geomares Publishing UK
- Engineering Surveying Showcase, Geomares Publishing UK
- Civil Engineering Surveyor, ICES Publishing, UK
- GIM International, Geomares Publishing, the Netherlands

There are a number of regular conferences where research on laser scanning and its application is presented and comprehensive proceedings are published, for example via the following:

- *International Archives of Photogrammetry and Remote Sensing* (ISPRS) provides the proceedings for the main congress (held every 4 years) and for the mid-term symposia for each of the technical commissions.

http://www.isprs.org/publications/archives.aspx

- The International Committee for Architectural Photogrammetry (CIPA) Symposia is held every two years and the proceedings of these symposia can be found on the ISPRS website.

http://www.isprs.org/publications/archives.aspx

- 3D ARCH – 3D Virtual Reconstruction and Visualisation of Complex Architectures is held every 2 years and the proceedings of these symposia can be found on the ISPRS website.

http://www.isprs.org/publications/archives.aspx

7.5 Websites

7.5.1 General information

At the time of writing the following websites provide useful information:

- ADS

ARCHSEARCH is an integrated online catalogue indexing over 1.3 million metadata records, including ADS collections and metadata harvested from UK historic environment inventories. The ADS Library brings together material from the British and Irish Archaeological Bibliography (BIAB), the ADS library of unpublished fieldwork reports as well as documents from the ADS archives and archaeological publishers such as Oxbow.

http://archaeologydataservice.ac.uk/archsearch/

http://archaeologydataservice.ac.uk/library/

- Historic England's Geospatial Imaging Team

The Historic England webpages provide information on all aspects of measured survey with links to other sites and publications, including a research report that compares laser scanning and SfM photogrammetry (Sou 2016).

https://historicengland.org.uk/research/methods/terrestrial-remote-sensing/specialist-survey-techniques/

http://research.historicengland.org.uk/Report.aspx?i=15545

- Historic England's Airborne Remote Sensing Team

The Historic England webpages provide information on the team's aerial archaeology survey work, including airborne laser scanning, such as a recent report on the use of existing Environment Agency lidar data and the tools required to exploit it for archaeological purposes (Crutchley and Small (2016).

https://historicengland.org.uk/research/methods/airborne-remote-sensing/lidar/

http://research.historicengland.org.uk/Report.aspx?i=15437

- Environment Agency

Information on the site referred to in Crutchley and Small (2016) and the jpeg imagery of the lidar data are available on the Environment Agency's webpages.

http://environment.data.gov.uk/ds/survey/index.jsp#/survey

https://www.flickr.com/photos/environmentagencyopensurveydata/albums/

- Laser Scanning Internet Forum

This is very useful and informative site that discusses technical issues as they arise and receives announcements from manufacturers.

https://www.laserscanningforum.com/

- Lidar News

This is a USA-based news and blog site for all aerial and terrestrial scanning news and discussions.

http://lidarnews.com/

http://blog.lidarnews.com/

- Geo-matching

This website lists and compares a whole range of survey equipment and software, although not all manufacturers supply information to it.

http://geo-matching.com/

7.5.2 Supplier information

The following provides links to the manufacturers of hardware and software referred to in the main text, but please note that this does not provide an exhaustive list of suppliers nor is Historic England specifically endorsing any of these suppliers.

7.6 Training

Manufacturers, equipment suppliers and survey companies provide training in the use of laser scanning devices and software. Training may also be required in associated skills, such as surveying control networks or photography. A good starting point for general survey training is the Survey School of The Survey Association (see section 7.2).

Supplier	Hardware/Software	Found at
3D Laser Mapping Ltd	ROBIN	http://www.3dlasermapping.com/robin/
Agisoft	Photoscan	http://agisoft.com/
AICON 3D Systems GmbH	PrimeScan	http://aicon3d.com/products/aicon-scanner/primescan/at-a-glance.html
	SmartScan	http://aicon3d.com/products/aicon-scanner/smartscan/at-a-glance.html
	StereoScan neo	http://aicon3d.com/products/aicon-scanner/stereoscan-neo/at-a-glance.html
ASUS	ZenFone AR	https://www.asus.com/Phone/ZenFone-AR-ZS571KL/
Atlas Computers Ltd	SCC	http://atlascomputers.ie/
Autodesk Inc.	3ds Max®	https://www.autodesk.co.uk/products/3ds-max/overview
	AutoCAD®	https://www.autodesk.co.uk/products/autocad/overview
	Meshmixer	https://www.meshmixer.com/
	ReCap™ Pro	https://www.autodesk.com/products/recap/overview
		https://lasers.leica-geosystems.com/blk360
	Revit®	https://www.autodesk.co.uk/products/revit-family/overview
Bentley®	Pointools	https://www.bentley.com/en/products/product-line/reality-modeling-software/bentley-pointools

Supplier	Hardware/Software	Found at
CloudCompare	CloudCompare	http://cloudcompare.org/
		http://www.danielgm.net/cc/
DAT/EM® Systems Int.	Summit Evolution	http://www.datem.com/summit-evolution/
DAVID®/HP Co.	DAVID Vision Systems SLS	http://www8.hp.com/us/en/campaign/3Dscanner/overview.html?jumpid=va_t1345uf8k6
Digital Surf	MountainsMap®	http://www.digitalsurf.fr/en/mntspm.html
DJI	Phantom 3 Professional	https://www.dji.com/phantom-3-pro
DotProduct LLC	DPI-8X	https://www.dotproduct3d.com/dpi8x.html
Esri®	ArcGIS	https://www.arcgis.com/features/index.html
FARO®	Focus^s/Focus3D	http://www.faro.com/en-us/products/3d-surveying/faro-focus3d/overview
		http://www.iqlaser.co.za/files/04ref201-664-en---faro-laser-scanner-focus-s-350-tech-sheet.pdf
	Freestyle3D X	https://www.faro.com/en-gb/products/construction-bim-cim/faro-scanner-freestyle3d-x/
	PointSense Family	https://www.faro.com/products/construction-bim-cim/faro-pointsense/
		http://download.faro-3d-software.com/DOCs/TechSheets/EN-FARO-PointSenseHeritage-TechSheet.pdf
		https://www.faro.com/products/construction-bim-cim/faro-pointsense/features/
	SCENE	http://www.faro.com/en-us/products/faro-software/scene/overview
	SCENE LT	http://www.faro.com/faro-3d-app-center/stand-alone-apps/scene-lt
	WebShare Cloud	https://www.faro.com/en-gb/products/construction-bim-cim/scene-webshare-cloud/
Geomagic®	Wrap®	https://www.3dsystems.com/software/geomagic-wrap

Supplier	Hardware/Software	Found at
GeoSLAM Ltd	Cloud	http://www.geoslam.com/software-products/geoslam-cloud/
	Desktop	http://www.geoslam.com/software/geoslam-desktop/
	ZEB-CAM	https://geoslam.com/wp-content/uploads/2017/08/GeoSLAM-ZEB-CAM.pdf
	ZEB-REVO	http://www.geoslam.com/hardware-products/zeb-revo/
Golden Software LLC	Surfer	http://www.goldensoftware.com/products/surfer
Google	Tango	https://developers.google.com/tango/
GoPro Inc.		https://gopro.com/
Harris®	Geiger-mode lidar	https://www.harris.com/solution/geiger-mode-lidar
IMAGINiT Technologies	Scan to BIM™	http://www.imaginit.com/software/imaginit-utilities-other-products/scan-to-bim
Kaarta Inc.	Contour™	http://www.kaarta.com/contour/
Leica Geosystems AG	BLK360	http://leica-geosystems.com/products/laser-scanners/scanners/blk360
	CloudWorx	http://leica-geosystems.com/products/laser-scanners/software/leica-cloudworx/leica-cloudworx-microstation
		http://leica-geosystems.com/products/laser-scanners/software/leica-cloudworx/leica-cloudworx-autocad
		http://leica-geosystems.com/products/laser-scanners/software/leica-cloudworx/leica-cloudworx-revit
	Cyclone	http://leica-geosystems.com/products/laser-scanners/software/leica-cyclone
	Cyclone REGISTER 360	https://leica-geosystems.com/products/laser-scanners/software/leica-cyclone/leica-cyclone-register-360
	JetStream	https://leica-geosystems.com/products/laser-scanners/software/leica-jetstream
	LiDAR Survey Studio™	http://leica-geosystems.com/products/airborne-systems/software/leica-lidar-survey-studio

Supplier	Hardware/Software	Found at
Leica Geosystems AG (continued)	Pegasus:Backpack	http://leica-geosystems.com/en-gb/products/mobile-sensor-platforms/capture-platforms/leica-pegasus-backpack
	Pegasus:MapFactory	http://leica-geosystems.com/products/mobile-sensor-platforms/software/leica-pegasus-mapfactory
	Pegasus:Two	http://leica-geosystems.com/products/mobile-sensor-platforms/capture-platforms/leica-pegasus_two
	ScanStation P40	https://leica-geosystems.com/en-gb/products/laser-scanners/scanners/leica-scanstation-p40--p30
		https://leica-geosystems.com/en-gb/products/laser-scanners/scanners/leica-scanstation-p50
		http://surveyequipment.com/assets/index/download/id/457/
	SPL100	http://leica-geosystems.com/products/airborne-systems/lidar-sensors/leica-spl100
	TruView	http://leica-geosystems.com/products/laser-scanners/software/leica-truview-global
Lenovo™	Phab 2 Pro	https://www3.lenovo.com/gb/en/tango/
LFM Solutions Ltd	NetView™	https://www.lfmsoftware.com/solutions/products/lfm-netview/overview/
Matterport	Pro2 3D	https://matterport.com/pro2-3d-camera
McCarthy Taylor Systems Ltd	LSS	https://www.dtmsoftware.com/
MeshLab	MeshLab	http://www.meshlab.net/
MicroSurvey®	STAR*NET	http://www.microsurvey.com/products/starnet/
NCTech Ltd	iSTAR	https://www.nctechimaging.com/istar/
	LASiris VR	https://www.nctechimaging.com/lasiris/
Nodal Ninja®	Extension pole	http://shop.nodalninja.com/
Orbit Geospatial Technologies	Orbit 3D Mapping	https://orbitgt.com/mobile-mapping/

Supplier	Hardware/Software	Found at
RIEGL®	RiANALYZE	http://www.riegl.com/products/software-packages/rianalyze/
		http://www.3dlasermapping.com/riegl-uav-laser-scanners/
	RiCopter	http://www.riegl.com/products/unmanned-scanning/ricopter/
	RiPROCESS	http://www.riegl.com/products/software-packages/riprocess/
	RiSCAN PRO	http://www.riegl.com/products/software-packages/riscan-pro/
	VMX-1HA	http://www.riegl.com/nc/products/mobile-scanning/produktdetail/product/scanner/53/
	VUX-1 UAV	http://www.riegl.com/products/unmanned-scanning/riegl-vux-1uav/
	VZ-1000 (superseded by VZ-2000i)	http://www.riegl.com/nc/products/terrestrial-scanning/produktdetail/product/scanner/58/
	VZ-400i	http://www.riegl.com/nc/products/terrestrial-scanning/produktdetail/product/scanner/48/
		http://www.riegl.com/uploads/tx_pxpriegldownloads/RIEGL_VZ-400i_Infosheet_2017-09-08.pdf
	VZ-6000	http://www.riegl.com/nc/products/terrestrial-scanning/produktdetail/product/scanner/33/
Routescene®	LidarPod®	http://www.routescene.com/products/product/uav-lidarpod/
	LidarViewer	http://www.routescene.com/products/product/lidarviewer/
SITECO Informatica srl	Sky-Scanner	http://www.sitecoinf.it/en/solutions/sky-scanner
SpheronVR	SpheronLite	https://www.spheron.com/products/point-cloud-colourisation.html
Basic Software Inc.	Surphaser	http://www.surphaser.com/
Teledyne Optech Inc.	Maverick	http://www.teledyneoptech.com/index.php/product/maverick/
Terrasolid Oy	Terrasolid Products	https://www.terrasolid.com/home.php

Supplier	Hardware/Software	Found at
Topcon	GLS-2000	https://www.topconpositioning.com/mass-data-and-volume-collection/laser-scanners/gls-2000
	IP-S3	https://www.topconpositioning.com/mass-data-and-volume-collection/mobile-mapping/ip-s3
	ScanMaster	https://www.topconpositioning.com/software/mass-data-collection/scanmaster
Trimble Inc.	MX2	https://geospatial.trimble.com/products-and-solutions/mx2
	RealWorks	https://geospatial.trimble.com/products-and-solutions/trimble-realworks
	SX10	https://geospatial.trimble.com/products-and-solutions/sx10
	TX8	http://www.trimble.com/construction/TX8_scanner.aspx
Velodyne LiDAR®	HDL-32E	http://velodynelidar.com/hdl-32e.html
	Puck LITE™	http://velodynelidar.com/vlp-16-lite.html
VIAMETRIS	vMS 3D	http://www.viametris.com/wcms/file/903-VIAMETRIS_-_vMS3D_v1_Leaflet_EN.pdf
Z+F®	IMAGER®	http://www.zf-laser.com/Z-F-IMAGER-R-5006h.3d_laserscanner1.0.html?&L=1
		http://www.zf-laser.com/Z-F-IMAGER-R-5010.3d_laserscanner0.0.html?&L=1
		http://www.zf-laser.com/Z-F-IMAGER-R-5016.184.0.html?&L=1
		http://www.zf-laser.com/fileadmin/editor/Datenblaetter/Z_F_IMAGER_5010X_System_Requirements_E_FINAL.pdf

7.7 Contact Historic England

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Acknowledgements

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2011 edition by Professor Jon Mills and David Andrews (Historic England)

2018 edition by Clive Boardman (Imetria Ltd/University of York) and Paul Bryan (Historic England)

Case study contributors and contact details:

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Web: www.ahr-global.com

Case Study 2: Rhineland – countermarks on Roman coins
Supplied by the Archaeological State Heritage Office of Saxony, Dresden
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Germany
Tel: +49 3518926807
Email: Thomas.Reuter@lfa.sachsen.de
Web: www.archaeologie.sachsen.de

Case Study 3: The Parthenon Frieze – comparative 3D scanning of the original sculptures and historical casts
Supplied by Dr Emma Payne, courtesy of the Trustees of the British Museum and Acropolis Museum.
UCL Institute of Archaeology
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Case Study 4: Cantabria – rock art in El Mirón Cave
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s/n, 08193 Bellaterra,
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Spain
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Case Study 5: The Iron Bridge – 3D modelling
Supplied by Tony Rodgers, Managing Director
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Case Study 6: Liverpool Street Station – BIM survey

Supplied by Jana Honkova, BIM Projects Manager
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Case Study 7: Tregony – survey of a historic walled garden

Supplied by Laura O'Connor, Geomatics Officer
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Email: laura.o'connor@cotswoldarchaeology.co.uk
Web: www.cotswoldarchaeology.co.uk

Case Study 8: Uphill Manor – combining terrestrial laser scan and aerial SfM point cloud data

Supplied by Charles Blockley, Senior Building Surveyor / Revit Technician
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Derby DE21 5DR
Tel: 01332 830044
Email: charlesb@greenhatch-group.co.uk
Web: www.greenhatch-group.co.uk

Case Study 9: Belsay Castle – laser scan survey

Supplied by David Andrews and Jon Bedford
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Email: david.andrews@HIstoricEngland.org.uk, jon.bedford@HistoricEngland.org.uk
Web: www.HistoricEngland.org.uk

Case Study 10: Navajo National Monument – laser scanning and tactile 3D model

Supplied by Steve Sawdon, Director
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Email: steven.sawdon@iictechnologies.com
Web: www.iictechnologies.com

Case Study 11: Oxford – BIM survey for heritage

Supplied by Lewis Hook, Mobile Mapping Manager
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Case Study 12: Leicester Cathedral – scanning the interior

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Case Study 13: The Roundhouse – reality capture survey

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Case Study 14: Priory House – laser scanning and modelling

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Case study 15: The Barley Hall Hub – scanning of archaeological artefacts

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Case Study 16: London - highway mobile mapping

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HEAG155
Publication date: 1st Edition August 2007

Reissue date: 3rd Edition January 2018

Design: Historic England

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