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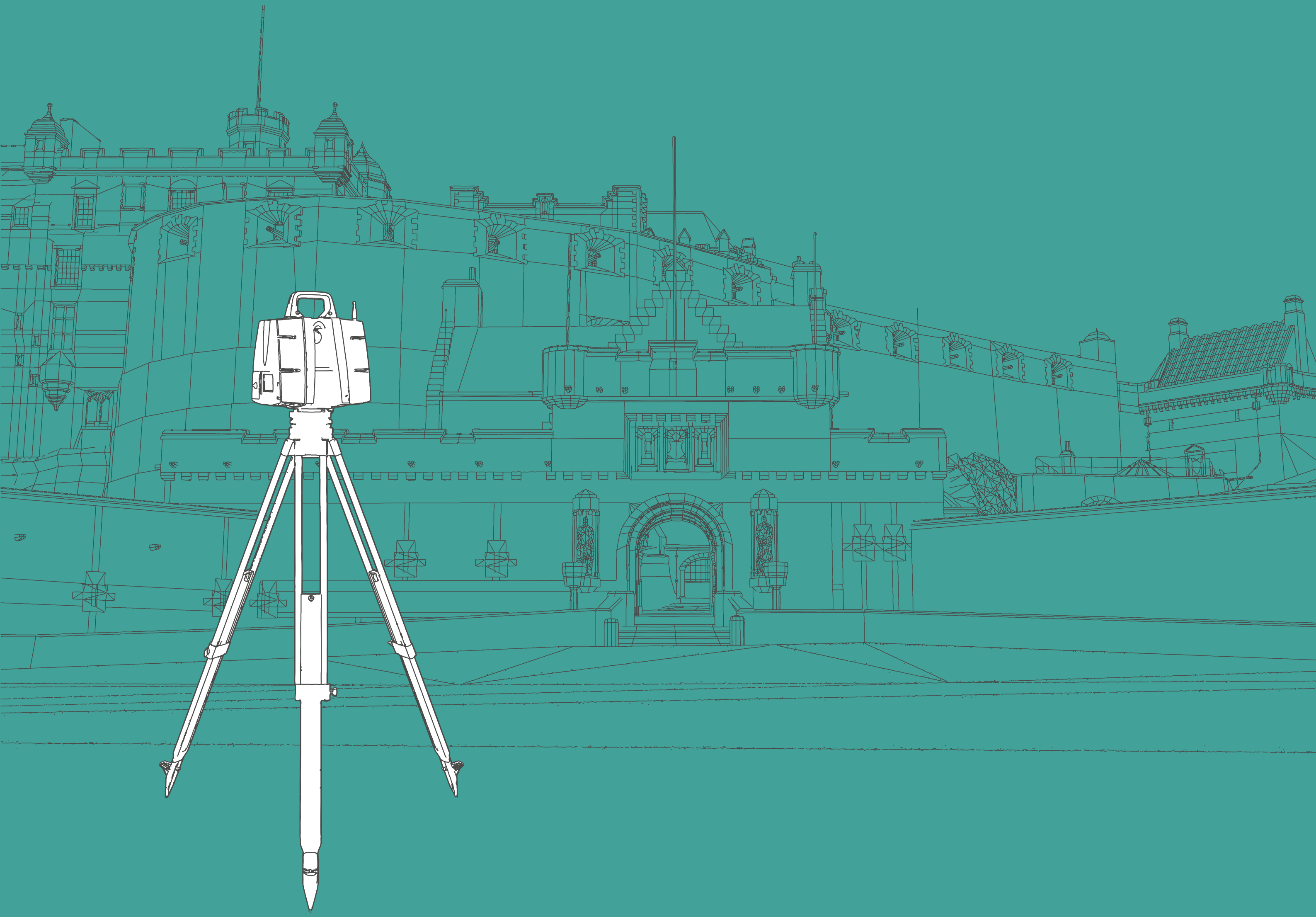
Short Guide

APPLIED DIGITAL DOCUMENTATION IN THE HISTORIC ENVIRONMENT



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Principal Author – Adam Frost

Editors – Dr Lyn Wilson, Alastair Rawlinson, Vanesa Gonzalez and Dr Ewan Hyslop

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Unless otherwise stated, all case studies are from projects undertaken by the Centre for Digital Documentation and Visualisation LLP (CDDV, a partnership between Historic Environment Scotland and The Glasgow School of Art).

This document includes a free augmented reality app for mobile devices, allowing readers to virtually explore 3D models of Rosslyn Chapel and the Nagasaki Giant Cantilever Crane cultural heritage sites. The 2D markers for the physical tracking of the models are included in the document appendices. Download our free Digital Documentation short guide companion app for Android and Apple iOS, search 'Digital Documentation.'

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1. INTRODUCTION

1.1. Aims

This document acts as a guide to how a broad range of data capture techniques can be applied to the recording, analysis, conservation and visualisation of the historic environment. This is the aim of 'digital documentation', which at its core is an approach to digitally recording objects, sites and even entire landscapes in their present condition. The uses and applications of these potentially enormous multi-layered datasets are numerous; a selection of which will be presented with relevant case studies. Each section will address fundamental principles and some best practices that should assist those looking to use digital documentation. The guidance should be helpful whether readers are intending to undertake a project themselves, from project planning to applications, or looking to engage the services of a third party.

1.1.1. Digital documentation

The principal types of data capture used within digital documentation (for example laser scanning) record the 3D surface properties of a subject through incremental measurements, representing the surface topology as a dense collection of discrete 3D points with XYZ coordinates. This is known simply as a point cloud. Unlike traditional survey methods applied within the field of cultural heritage, such as hand drawn or total station building plans and elevations which typically aim to record distinct features (e.g. windows, door frames, lintels), point clouds generated through scanning are a record of the surface sampled indiscriminately at regular intervals. The level to which distinct features are visible in this point cloud is a result of the resolution and accuracy it was captured at, which should be decided before undertaking any data capture.

Within the context of a survey, this same point cloud dataset could then be used for spatial or dimensional analysis, or to create further outputs in a range of different formats such as detailed 2D drawings, 3D models for visualisation or Building Information Modelling (BIM). Regardless of the application, any scheme of work should start with a well-defined specification for the work to be undertaken, tailored to the intended purpose of the dataset.

1.1.2. Uses and applications

Through a series of case studies that explore a range of different applications for digital documentation, we take an experience-led look at how these datasets can enable unique types of analysis and enrich existing techniques. Monitoring and mapping change within the built and natural environment is one example, where the impact of natural erosion effects from weathering and climate change can be evaluated and used as a decision making tool to mitigate further change. With proper control, the 3D data can help quantify change over time (including volumetric calculations), visualise dimensional differences and highlight areas of interest. Applied to buildings, this same approach can be used to identify structural changes such as movement, surface erosion and alterations, aiding assessments of structural stability and informing conservation strategies.

By adding layers of data generated by other techniques such as thermography and moisture mapping, we can develop a more sophisticated picture of how specific buildings operate, informing decision making for future conservation and improving environmental performance. Part of this process is visualising these datasets, and interpreting the results generated is important to both the expert and the layperson.

A key feature of digital documentation is that it offers a relatively unified platform from which to convey the information, whether it is via basic rendering of the raw data or the creation of a detailed 3D model. There are few limits to how complex the data can be. The focus should always be to convey a result that most accurately and coherently reflects the dataset.

1.2. Quick start digital documentation checklist

The decision to use digital documentation should be the result of an informed look at available approaches to best recording specific objects and sites. Prior to commissioning or undertaking any system of survey work, it is vital to understand the intended outcomes and applications of the expected results. The specification of the survey, fieldwork methodology and the quality of deliverables generated revolves around this initial assessment. To assist with this process, a number of key conditions are presented for the consideration of those looking to utilise digital documentation as a key component or basis for their project.

Planning and preparation
Outline the primary objectives of the project and the specific role of digital documentation.
Identify the appropriate techniques (see section 2) for data capture.
State the requirements of the project within a specification. This should describe the parameters of any survey or scheme of data capture, including resolution, tolerance (accuracy), coverage and additional data (such photo-texturing to overlay terrestrial laser scanning). Aim to tie into existing control networks where possible.
Structure the data capture, processing and creation of deliverables as work packages that may be undertaken separately.
Address logistical aspects such as access to the site or object, handling (if appropriate) and health and safety requirements.
Allow for contingency to account for uncontrollable factors that may impact the project such as inclement weather or impeded physical access.
Methodology
Design the data capture methodology to accomplish the stated objectives and deliver a dataset that meets the specification criteria. This scheme of work can be defined within a Risk Assessment and Method Statement (RAMS) document.
Arrange a skilled team or individual to undertake the scheme of work, ensuring the equipment and methodology meets the requirements earlier identified. This should be included in the RAMS document.
Collect relevant metadata throughout the entire data capture and processing stages. This acts as both a detailed record of the project steps and a useful tool to aid further processing and utilisation of the dataset.
Clearly define the desired deliverables to be produced from the dataset, e.g. 2D CAD drawings, photo-textured 3D model. Ensure that these deliverables adhere to defined tolerances where necessary.
Data management and dissemination
Incorporate a level of quality control into all stages of data capture, processing and delivery of outputs. If a scheme of work is undertaken by a third party/external contractor (for example, a laser scanning survey), acceptance of the data should be conditional subject to review.
Consider the channels and formats available for dissemination of the data.
Ensure that data made publically available and/or released to third parties is at minimum covered by a suitable and explicit arrangement, e.g. license agreement, statement of IPR, open access.
Plan to maintain and archive raw and processed datasets that may require substantial storage capacity.

2. DATA CAPTURE AND PROCESSING

Choosing the appropriate techniques to undertake a scheme of digital documentation depends principally on the scale of the subject, the intended purpose of the dataset and the requirement for additional data (beyond spatial). The following table presents a categorised view of a number of 3D capture techniques regularly employed to record the natural and cultural environment. Due to variation between different systems of the same type, stated accuracies and ranges should only be treated as broadly representative.

2.1. Spatial data capture techniques overview table

Scale	Specific technique	Relative accuracy	Produced data type
Landscape [>km]	Interferometric Synthetic Aperture Radar (InSAR)	≥300mm*	Spatial (XYZ), intensity
	Airborne LiDAR	30mm	Spatial (XYZ), intensity, photo (RGB), orthophoto, classified
	Mobile laser scanning, e.g. boat/vehicle mounted system	20mm	Spatial (XYZ), intensity, photo (RGB)
	Aerial photogrammetry, e.g. unmanned aerial system (UAS), aircraft	30mm**	Spatial (XYZ), photo (RGB)
Structure [<km]	Terrestrial laser scanning (TLS)	3mm	Spatial (XYZ), intensity, photo (RGB)
	Total/Multi-Station	2mm	Spatial (XYZ), photo (RGB)
	Global Navigation Satellite System (GNSS)	1-5mm	Spatial (WGS84)
	Simultaneous Localisation and Mapping (SLAM)	30mm	Spatial (XYZ), intensity, photo (RGB)
	Structure from Motion (SfM) Photogrammetry	3mm**	Spatial (XYZ), photo (RGB)
Object [<m]	Structured light scanning	0.1mm	Spatial (XYZ), photo (RGB)
	Triangulation laser scanning	0.05mm	Spatial (XYZ), photo (RGB)
	Structure from Motion (SfM) Photogrammetry	0.1-2mm**	Spatial (XYZ), photo (RGB)
	Reflectance Transformation Imaging (RTI)	n/a	Photo (RGB), normal map
	Reflectance Transformation Imaging (RTI)	n/a	Photo (RGB), normal map
Marine	LiDAR Bathymetry [>km]	200mm	Spatial (XYZ), intensity
	Structure from Motion (SfM) Photogrammetry [<m]	2mm	Spatial (XYZ), photo (RGB)

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* Accuracy refers to DEM derived from InSAR.
** Results depend significantly on subject geometry, quality and quantity of input images, camera specification and Ground Sample Distance (GSD).

2.1.1. Selecting methodology

Priority should be given to the methodology that best fulfils the project specification, uses the most appropriate techniques where there are overlapping options and ensures an accurate and useful end product. This decision making process may also be time and cost driven, ruling out options that may come with a greater upfront cost or are logistically impractical. It is important to bear in mind that any programme of data capture will also have an associated processing overhead to deliver the dataset, which should be accounted for in any comparisons.

The following section will break down some of the key planning and methodological issues for consideration when either undertaking a scheme of digital documentation directly or via a third party.

2.2. Survey specification

A specification is the foundation for any body of work to be undertaken, defining the key parameters and aims of the project for those involved.

2.2.1. Existing specifications

Whilst there may be advantages to developing a bespoke specification for a project that uses digital documentation, it is worth exploring existing standards that may apply. The Metric Survey Specifications for Cultural Heritage (2015) developed by Historic England (formerly English Heritage) are a detailed and thorough example, particularly for the application of terrestrial laser scanning and photogrammetry to survey within the historic environment.

2.2.2. Purpose and brief

Clearly state the objectives that the scheme of digital documentation will be looking to achieve and its application. One such example could include the complete interior and exterior capture of a historic site to create a geo-referenced laser scanning dataset that incorporates existing survey control markers. An alternative example could be the photogrammetric documentation of a collection of archaeological artefacts to create a detailed measured 3D record intended for online dissemination.

2.2.3. Tolerances (accuracy and precision)

Two important concepts that require distinction in the field of spatial data capture are accuracy and precision. Accuracy refers to how close a measured value is to the true value. Precision refers to the likelihood that repeated measurements will have a similar or identical value. The specification of survey equipment should be explicit about these attributes, and some equipment will perform better than others. It is important that the tolerances of the equipment employed for a survey at the very least meets or exceeds the data capture requirements. These can usually be found in the manufacturer documentation.

Accuracy may also be defined in ‘relative’ and ‘absolute’ terms. Relative accuracy refers to the known tolerance of the specific device within stated conditions, e.g. a terrestrial laser scanner at 50m. Absolute accuracy is the value that defines how closely measurements from the dataset reflect real world values.

2.2.4. Resolution

The resolution of a dataset will govern which features and details can be identified. It can be defined broadly by the frequency and distribution of data points across a surface. The target resolution should be determined by the desired outcomes; if a dataset should be used to produce detailed architectural CAD drawings, a specification will look for ≤10mm point-spacing (i.e. requiring a minimum of one measurement every 10mm). For topographic plans or a Digital Elevation Model (DEM), a resolution ≥250mm may suffice. It is worth noting that whilst capture devices typically have upper resolution limits that may be limited by their design or relative accuracy, they will often allow capture at a lower resolution for flexibility. Attention should be paid to the capability and tolerances of the capture techniques, which may be unsuitable for delivering the desired resolution. Refer to the table in section 2.1 for a quick guide to selecting the appropriate method.

2.2.5. Coordinate system

It may be a requirement of the project to situate the captured data within a specific coordinate system, such as a local site grid or the Ordnance Survey National Grid (OSNG). Spatial data defined by XYZ coordinates can be transformed to a known local coordinate system through capturing control points in common with pre-existing survey work, such as established permanent survey markers. By using Global Navigation Satellite System (GNSS) or known geo-referenced points, the digital dataset can also be transformed to a variety of other national or global coordinate systems such as the World Geodetic System 1984 (WGS84) or the Ordnance Survey National Grid (OSNG).
This topic is covered in greater detail in section 2.6.1.

2.2.6. Coverage

This is the extent of how much of the site or object(s) will be captured. Coverage can be defined as the bounds or completeness of a survey, and may depend on a range of techniques and methodologies. Typically, the aim within digital documentation is to maximise data capture coverage of a site or object. In the context of a survey for example, this might be denoted by an established topographic boundary for the site, areas that are physically inaccessible, or limiting the capture to interior or exterior spaces only. To maximise coverage in areas that are difficult to access, an alternate or additional approach may need to be considered. This may include the use of Unmanned Aerial Systems (UAS), specially designed equipment to extend or elevate capture devices, or employing trained rope access teams to capture high level detail.

2.2.7. Internal and external use

A specification should be used and referred to by project stakeholders, whether undertaking the work directly or commissioning a third party such as an external contractor. This ensures that the correct results are achieved and that the final datasets and deliverables are fit for purpose, whilst also helping to avoid problems such as a ‘scope creep’ and improve project management estimates. For contracting, the same specification can be used as part of the tender process to convey the project requirements for quotations, and ensure adherence to provided standards.

2.3. Risk Assessment and Method Statement (RAMS)

For projects that involve on-site work or object handling that could present safety risks, a risk assessment should be developed in tandem with a method statement prior to undertaking any on-site work. For a risk assessment, potential specific risks should be identified and met with safety control measures to develop a safe system of work. After work commences, it should remain a dynamic document, open to reassessment by those conducting the work. Employers and employees should be aware of The Health and Safety at Work Act 1974, which is the primary legislation within the UK governing the safety of operations, welfare and training and other issues within the working environment.

A method statement will outline specific work activities that may incur risks to safety, including the identification of access requirements to specific areas. Look to your own company's policy for further information and guidance on assembling the RAMS and available templates.

2.4. Project outputs and deliverables

Project deliverables are decided from the outset, and typical examples might include the following:

- Processed, registered point cloud from a metric survey (e.g. terrestrial laser scanning or photogrammetric)
- Photo-textured 3D model(s) of objects for mobile or online dissemination
- Set of Computer Aided Design (CAD) drawings of building elevations and plans
- Calculations of volume and area for specific features or objects
- Visualisation of change over time (4D) from a program of environmental monitoring
- 3D models or content for an interactive 3D game on a computer or mobile (phone or tablet) platform, including serious games applications such as training in a virtual reality (VR) environment using VR headset technology

The capture methodology should be designed around providing the correct dataset for the creation of the principal deliverables. For example, a scheme of monitoring for a building or environment will require a measured dataset with an accurate survey control network that can be re-established periodically, perhaps including geo-referencing to the Ordnance Survey National Grid. Alternatively, a project looking to visualise and enable virtual access to artefacts in a museum collection, or create 3D assets for a game, may not necessitate accurate real-world scaling, but require a controlled lighting setup to obtain robust photography. It is important that any specified deliverables are completed to relevant standards, which should be defined beforehand and may vary between countries, disciplines and intended the application.

Projects should be explicit about the number and types of deliverables and the level of information conveyed (e.g. 2D drawings at different scales, Building Information Models (BIM) at different Level of Details, etc). These are key factors in calculating costs and time budgets for assigned tasks, and should not exceed the initial requirements unless otherwise stated.

The strength of digital documentation is the ability to reuse datasets for a multitude of purposes, and users should balance the need to capture detailed raw data with the requirements of the deliverables. The likelihood that higher level of detail deliverables may be required in the future should also be factored in to the planning of the data capture specification.

2.5. Data management, metadata and archiving

Digital documentation emphasises the capture of high resolution, multi-layered datasets. Whereas traditional 2D vector drawn records for example require very little storage capacity, some techniques such as laser scanning and photogrammetry yield vast raw datasets that are processed and output to further large datasets and digital assets. Prior to undertaking a scheme of digital documentation, ensure that there is provision to store, archive and disseminate potentially terabytes of data. This largely depends on project requirements, intended deliverables and the scale and complexity of the site(s) or object(s).

Data management for projects should aim to design and maintain a well-structured system of files with pertinent metadata. Organising data hierarchically by 'raw', 'processed' and 'outputs' will help distinguish data generated at different stages of the project. Raw data can be filed via a number of different parameters, including date/time or capture session, methodology, capture technique or specific instrument. Processed data might be ordered by iterations or stages of completion for example, and specific technique where mixed datasets have been created. Outputs or deliverables can be separated by file type, iteration, and resolution such as where higher or lower resolution versions of the same dataset have been produced.

During the planning phase of a project, be explicit about the rights of ownership of produced datasets, photographs of the documentation process and any produced deliverables. This is critical if working with third parties, commissioning or subcontracting a scheme of work. Ensure that permission is sought where necessary if the data is published or disseminated, and that any channels for distribution of the data or outputs are clear about licensing and terms of usage (if applicable). If the site or scheme of work is sensitive, consider incorporating non-disclosure agreements into the contractual process. If transferring the dataset partially or in its entirety between organisations, consider the use of a formal transfer agreement to specify rights, usage and liability.

2.5.1. Archiving vs storage

A project should recognise the distinction between storage of the data and archiving it as a record. Archiving refers to the system that ensures the dataset continues to be usable, both in its integrity (security from data corruption) and in compatibility with the currently employed systems and software packages. Users should look to their organisation's policy and system for archiving, and ensure it meets their requirements to undertake a project or body of work. For reference, the Open Archival Information System (OAIS) provides a standard and model (ISO 14721:2012) for the broader activities involved in digital preservation of information.

Archival processes should monitor the data to detect change or corruption, and a key method is the use of checksum algorithms, which produce a 'signature' for files based on the input data. For greater security, users should maintain multiple redundant copies of the dataset stored in physically separate locations, ideally with offsite backups. Reuse of the data and its role as a record should be the objective of all digital documentation projects, though access requirements may be different such as for change-monitoring projects. The system should also consider the active migration of datasets to ensure compatibility with developing software environments and packages.

Further reading on archiving, data management and digital preservation of datasets is made available by the Digital Preservation Coalition (DPC). Much of this information can be accessed via their website (*www.dpconline.org*). The Archaeology Data Service also promotes standards, and provides guidance and resources for people looking to access or deposit archaeological datasets (*www.archaeologydataservice.ac.uk*).

2.6. Survey control

In the context of digital documentation, control represents any system that provides a stable frame of reference independent of the subject. In practice, this is usually incorporated as a survey control network: a series of known points that are stable, accurate and verifiable. If the survey control points have values in common with other coordinate systems, such as a local site grid, or the OSNG acquired via GNSS, the overall dataset can be transformed to a different coordinate system. A control network can also be used to improve the absolute accuracy of techniques that may develop compound error over longer distances, and provide a necessary baseline in situations with a changing environment.

2.6.1. Geo-referencing and coordinate systems

Coordinate systems are briefly discussed in sections 2.2.5 and 2.6, and remain a crucial part of understanding spatial data in any context. Manipulating data within a coordinate system, or changing from one coordinate system to another, is accomplished through using ‘transformations’. Some basic transformations commonly used within 3D work include translation, rotation and uniform scaling. For example, translation and rotation are key transformations for ‘registering’ (aligning) discrete terrestrial laser scans taken in different positions. Registering photogrammetric data to a measured dataset would additionally require scaling. Most software packages that work with 3D data will facilitate these operations, though the speed of the operations, the quality of the results and statistical reports will likely vary.

2.6.2. Global Navigation Satellite System (GNSS)

Another common transformation is from one coordinate system to another, as commonly seen with GNSS data. GNSS refers to the technology of using satellites to determine location, and often incorrectly used interchangeably with GPS (Global Positioning System). GPS is the US satellite constellation, which has military origins and was made available for civilian use in 1996. Other constellations include the Russian system GLONASS, the European system Galileo and the Chinese system BeiDou. Modern GNSS receivers will look to multiple constellations to improve the availability of satellites in the visible sky. For further reading on the topic of GNSS and coordinate systems, the Ordnance Survey as extensive information available via their website *www.ordnancesurvey.co.uk*.

The data is expressed in a global coordinate system - WGS84 (World Geodetic System 1984), though a compatible but more accurate European equivalent is ETRS89, which also factors in Eurasian continental drift. Two underlying concepts, the reference ellipsoid and the geoid model determine how heights are expressed. The reference ellipsoid refers to an approximation of the earth’s shape, whilst the geoid model more accurately depicts the organic, imperfect surface of the earth and can be used to calculate orthometric heights, i.e. relative to Mean Sea Level.

2.6.3. Scale factors

Using the available Ordnance Survey transformation OSTN15 (the updated version of OSTN02), and the geoid model OSGM15, GNSS data can be transformed from global coordinates to OSGB36 National Grid coordinates with orthometric heights. The process of moving from a 3D to a 2D method of representing space (such the National Grid) requires a projection, and should account for scale factor to mitigate projection distortions. This is a minor adjustment, but over larger distances becomes increasingly significant.

An example situation in digital documentation might be a scheme of laser scanning over several kilometres. In its fully processed and registered form, the data should be an accurate representation of the recorded area in 3D. It may be controlled by a Total Station traverse (for more detail see section 2.6.4) and also have several control points collected via GNSS to situate it on the OS National Grid. If the dataset is georeferenced without applying a scale factor, measurements taken from the dataset (such as plotting a road or structures) will likely differ noticeably from existing OSNG coordinates for these features, potentially up to 0.5m over 1km.

2.6.4. Total Station/Multi Station

Total Stations are LiDAR based survey instruments that enable highly accurate measurement of angles and distances over considerable range. They can be used to establish a control network of known positions throughout a site over distances of a kilometre, and can serve as the primary tool to accomplish a range of additional survey work such as setting out, taking levels and site monitoring. Multi Stations (Fig. 1) are a development of the Total Station, which bring additional functionality such as photography and laser scanning to the device. Measurements are taken using prisms (Fig. 2) or in a reflectorless configuration, which can capture points of data directly from a surface or be used in conjunction with a height offset to obtain an exact ground position.

Total Stations have a high accuracy specification (e.g. 1” arc) and may be used to enhance and quality-control a typical terrestrial laser scanning or photogrammetry survey. This can be accomplished by first establishing a series of ground points as the control network which may be temporary, semi-permanent (e.g. for the duration of the survey) or permanent (to be revisited in subsequent surveys) depending on the survey requirement. These established coordinates are then incorporated into the dataset via targets with a known offset from the ground points. Alternatively, capturing targets (Fig. 3) that are referenced within the dataset but may be independent of the environment or ground level.

Fig. 1 Leica Geosystems MS50 Multi-Station.

Fig. 2 A total station prism.

Fig. 3 Black and White target often used in terrestrial laser scanning.


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2.6.5. Traverse and re-section

The most effective methodology for establishing a control network via a Total Station (or instrument with similar functionality, such as some laser scanners) is to use a closed-loop traverse. This is commonly a sequence of measurements taken from setup to setup by taking foresights and backsights, using instrument and target heights to establish a point on the ground marking the setup location. Whilst traverses can be open or linear, a closed loop method provides a more robust approach by allowing the surveyor to calculate misclosure, and adjust and distribute angular error. Some key best practices include avoiding measured angles that are flat (~180º) excessively obtuse (>330°) or acute (<30°). The length of each leg of a traverse should be similar; no leg should be more than double the length of the shortest one. It is good practice to check measurements to control stations through repetition. Fig. 4 shows a plan view schematic of an example traverse with linked setups.

Resection is a technique to calculate the current setup position based on reference to two or more known points. As part of a laser scanning survey, it can be used for example to tie in additional laser scanning work whilst maintaining reference to the control network. Fig. 5 shows a schematic view of a resection setup, illustrating a linear traverse established from two known points.

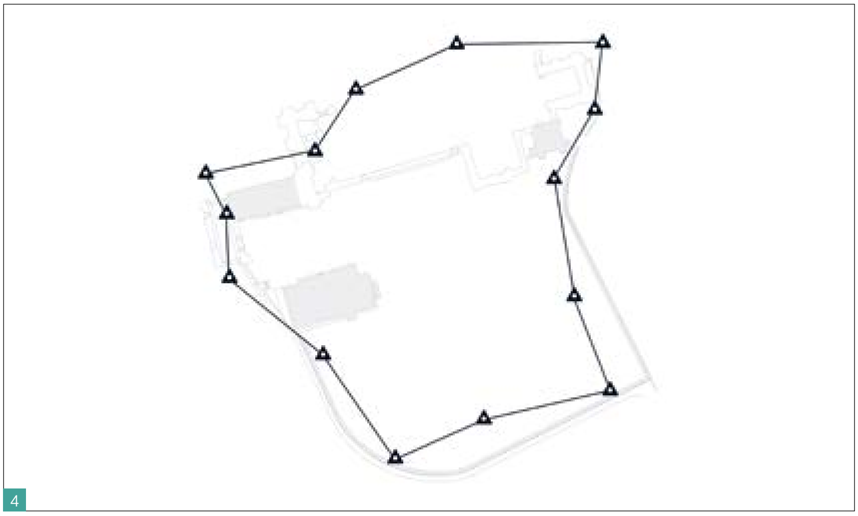

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Fig. 4 Illustrative diagram of a closed-loop traverse comprised of 14 setups. Setup positions are marked with triangular icons.

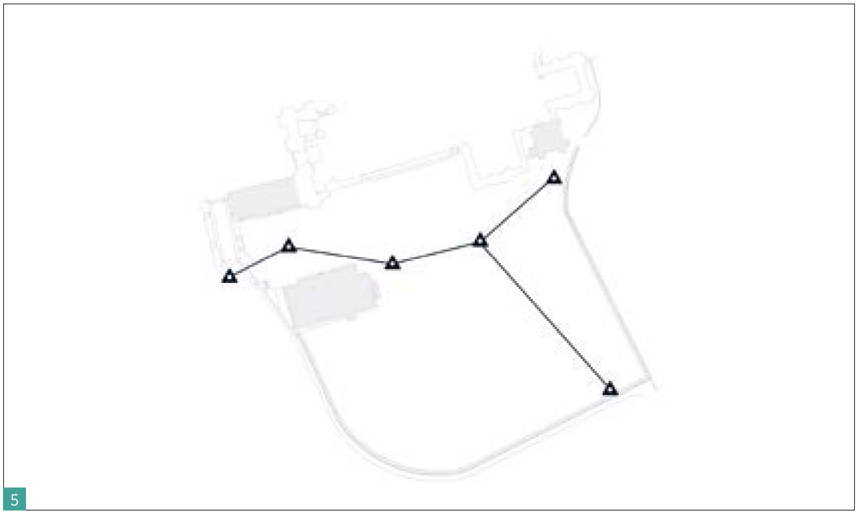

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Fig. 5 Illustrative diagram of a resection setup from two known stations.

2.7. Terrestrial Laser Scanning (TLS)

Within the field of digitally documenting the built and natural environment, terrestrial laser scanning is one of the core techniques that enable the rapid and accurate capture of high resolution 3D data. It is increasingly central within the surveyor's toolkit, particularly for specific types of survey where field time can be minimised and hazards associated with acquiring measured data in difficult to access areas can be reduced. Typically, these are tripod mounted systems (Fig. 6) that have established workflows for data capture, integration with control networks via targets, registration software and processing steps.

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Fig. 6 Terrestrial laser scanning at Arbroath Abbey.

The data produced is a collection of discrete measurements, often in the order of millions per scan, referred to as a 'point cloud' (see Fig. 7). Each individual point will have an XYZ coordinate, but potentially also Intensity (the strength of the returned laser beam) and RGB (Red Green Blue, a value derived from a photograph mapped to the point cloud).

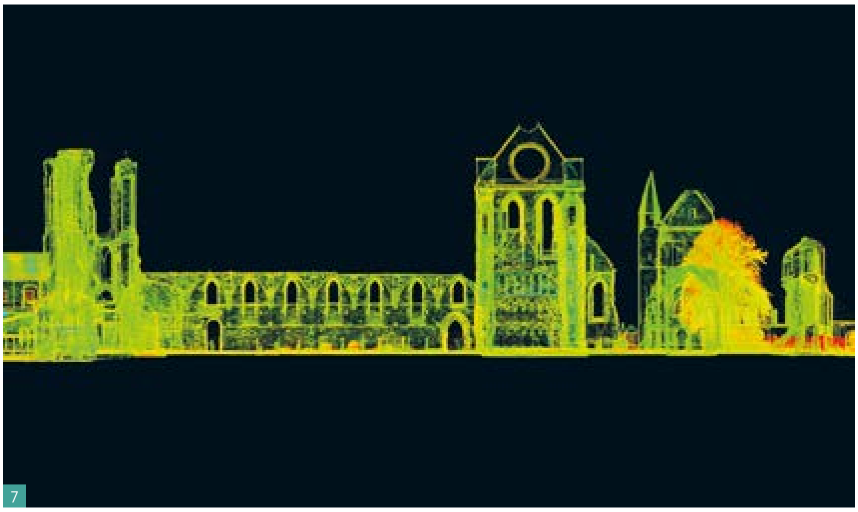

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Fig. 7 Orthographic point cloud image of Arbroath Abbey South elevation, displayed with intensity values and silhouette shading.

2.7.1. Principles of LiDAR

Terrestrial Laser Scanning utilises a technique known as LiDAR (Light Detecting and Ranging) to acquire measurements. This works by firing a beam of laser light at a surface and measuring its return properties to gauge distance between its origin and the object surface. Scanners spin a mirror to take measurements along vertical lines of data as they rotate, capturing the surrounding environment with a near-spherical line of sight. Traditionally, the two main categories of terrestrial laser scanner are determined by how they measure the return laser, which also informs the specification of the instruments, such as recommended and maximum range (distance to surface), and, to some extent, the quality of the data.

Time-of-Flight (or ‘pulse’ based) scanners measure the time between the initial firing and the return signal, dividing the elapsed period by the speed of light to calculate overall travel distance, then dividing by two to calculate the scanner’s distance to the surface.

Phase based (or phase shift) scanners identify the phase difference between the transmitted light and the returned light, determining the phase offset. This offset is a direct product of the distance travelled. The transmitted beam will typically be modulated to resolve the phase position.

The manufacturer’s specification should explicitly state the performance information of the scanner, including key information about the laser measurement component such as wavelength, spot size (beam divergence), range, speed and accuracy. This should help determine its application for different survey purposes. It is up to the user to ensure that the equipment meets the specification of survey and is capable of capturing the requisite quality of data. It is also worth considering other factors such as battery life, operating environmental performance (including Ingress Protection ratings) and the physical size and weight of the equipment. These attributes may determine outright whether a scanner can be used in a specific environment due to environmental factors such as physical access or temperature.

2.7.2. Limitations of Terrestrial Laser Scanning

Whilst TLS is a powerful measurement and survey tool, it should always be considered as one tool in a range of different methodologies and techniques. Some objects and environments may pose particular challenges that may better be captured with, or in tandem with, different techniques. Users should be aware of these limitations and plan a scheme of digital documentation accordingly.

2.7.3. Material properties

Laser scanners are optical systems that rely upon the return of the transmitted light; if this is interrupted, absorbed significantly, refracted or completely reflected the resultant data will be affected. The intensity of the returned laser signal is largely determined by the albedo of the surface, which is the ratio of absorbed to reflected light dictated by material properties. For example, scanning a light coloured masonry wall (which may have an albedo of 0.55 for example) will return a much stronger signal than if it were made from a much darker stone (charcoal for reference has an albedo around 0.04). As different scanners generally use different wavelengths for their lasers, a range of scanners might experience mixed results for the same surfaces and pigments. The strength of the reflected beam will directly affect the accuracy of the data captured, as poorer signal strength means a worse signal-to-noise ratio; this is often stated within the tolerances of the scanner documentation at different ranges.

Glossy painted and highly reflective surfaces are also known to generate extraneous data, often also referred to as 'noise', which is caused by incorrect returns. Glass and mirror-like surfaces can be particularly problematic, capturing the reflection visible in the surface rather than the mirror surface topology, which can require judicious use of filtering and cleaning of the final dataset. Transparent materials such as glass and water will also refract the transmitted light, generating unreliable data that may appear otherwise intact. Scattering materials such as marble or alabaster that are commonly encountered in cultural heritage are generally problematic; they may show noise or offset surfaces, likely due to subsurface scattering introducing unpredictable returns.

2.7.4. Physical access and environmental factors

TLS relies upon line of sight to the surface being recorded to successfully capture it. Planning a scheme of data capture should account for this; otherwise, coverage of the site will be poor, omitting important details such as building roof level or surfaces obscured by others. Obstacles to line of sight outside of the control of those undertaking the survey must also be accounted for, such as vehicles, foliage, temporary structures and members of the public at sites with public access and high footfall. Consideration should be given to undertaking the work during days when the site is closed to public access, during a different season when foliage or tree cover is less pronounced, and when weather best permits. Heavy fog will severely impede scanning and reduce the effective laser range, whilst snow cover will create extraneous data and block data capture.

2.7.5. Cost

There is a relatively high cost of entry for the use of TLS, with most modern commercially available scanners priced in the region of fifteen to seventy thousand pounds (prices valid at the time of publishing). New products, workflows and the overall development of technology is reducing this, and rental of equipment should be considered where suitable. Additional costs of software licensing, high performance computer hardware and support should be factored in. With this in mind, the speed and productivity benefits to how surveys can be undertaken lead to significant savings in field time, including savings for physical access and health and safety (such as the erection and maintenance of scaffolding) that may otherwise incur high costs.

2.7.6. Calibration

Scanning equipment that works within specified manufacturer's tolerances will typically require regular calibration to ensure it performs as expected. This may include returning the instrument to the manufacturer or a third party for calibration using specialist equipment or procedures, leading to downtime and incurring additional expense. This service should be supplied with a certificate stating that the instrument meets specification. The same may apply to the peripheral equipment such as tribrachs, which are used to provide a levelling surface between the tripod and the scanner. Some equipment also enables self-calibration which can be undertaken by the user, though it should be tested and found to meet specification before use.

2.7.7. Data capture methodology

To obtain the best possible coverage of a site as discussed in section 2.2.6, particularly with TLS, a range of different methodologies should be considered depending on the specification of the survey. If there are obstacles to physical access, solutions such as ropes access teams, elevated tripods and bespoke rigs may facilitate the capture of typically hidden surfaces.

The methodology should also consider how the data will be registered together (for further information on the alignment of data see section 2.7.8). This will necessitate either the use of targets between discrete scan positions and/or sufficient overlap of data to use 'feature' registration, wherein scans from different locations are registered together using captured data of the scanned environment. A target based system of registration may either use traditional survey methodology as discussed in section 2.6.5, such as traverse, or re-section where scans will be undertaken at different setup locations, though not all scanning instruments have this functionality on-board. Alternatively, targets can be placed strategically between scans or even throughout the entire site. The centre of the targets ('nodal point') must remain in the same position, which may mean either the targets remain static or they must be 'tilt and turn' style targets (see Fig. 3) that can rotate to follow the scanner whilst preserving the nodal point of the target. A minimum of two common targets is required to connect scan positions; with three or more targets, one can be used to 'leap frog' to tie in subsequent scans by leaving two targets static whilst each time moving the farthest to a new position. The maximum distance between the scanner and targets depends on the system specification and resolution at which the target is captured. Fig. 8 shows an example target arrangement to connect three terrestrial laser scanning setups.

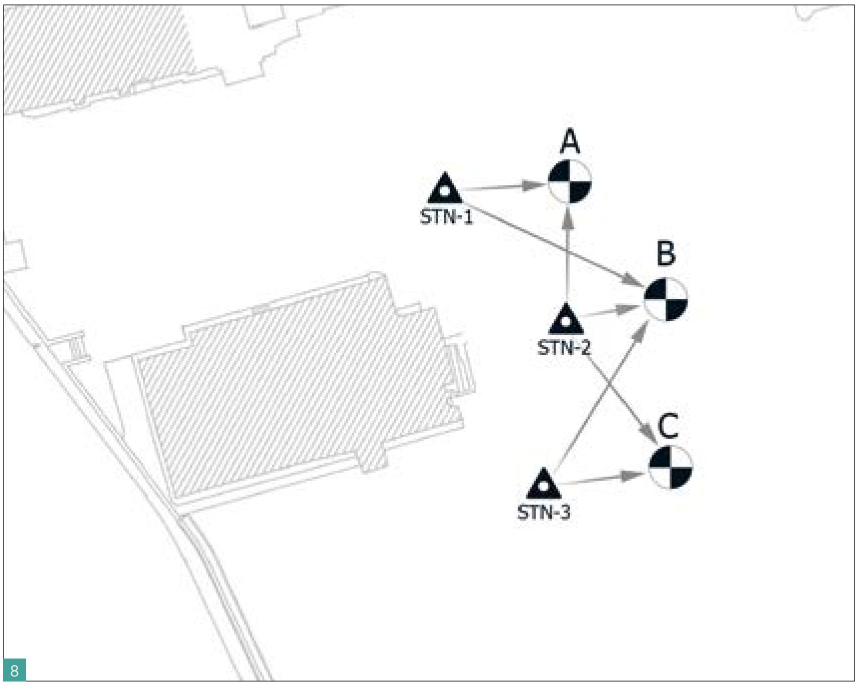

Fig. 8 Illustrative diagram of target arrangement on site.

Positioning of scans should be designed to maximise coverage whilst achieving the specified surface resolution. Most laser scanners will define different resolution settings. One example would be '10mm at 10m', which indicates one measurement every 10mm at a distance of 10m in a spherical grid around the nodal point. At 50m, this equates to a point spacing every 50mm, and 100mm at 100m. The higher the capture resolution, the greater the time necessary to complete the scan.

2.7.8. Data processing and registration

Capturing large quantities of spatial data for sites requires a structured and consistent approach to naming conventions. This should be agreed prior to undertaking significant or even minor projects, and essentially provide metadata, including a unique and identifiable project code. For example, naming scans in the format of 'Code_Location_Date_Increment', which on a larger project might refer to a sub-area, e.g. 'AB_Compound_140515_04'. When scanning, these names should be updated as often as is feasible to reflect the date and location. Raw data should be stored separately to processed datasets and use a logical and scalable folder structure.

2.7.9. Filtering

Laser scan data is often filtered to remove noise prior to integration with a registered dataset. Different types of filter exist to remove noise generated by different processes, and often use parameters defined by the user to vary the effect. As a range of conditions can create noise, there is rarely a 'silver bullet' filter or setting to leave only the pertinent data. However, some commonly used filters include Mixed Pixel and Intensity. Mixed pixels are points created when the laser beam falls on the edge or between surfaces, returning an ambiguous distance. This often appears as 'edge spray' as illustrated in Fig. 9. Fig. 10 shows the same dataset after filtering. Intensity filtering allows the selective removal of points that fall within a specified range. This may be useful if trying to remove a large quantity of erroneous or unwanted data, such as that with poor signal returns, especially if removing it manually using selection tools would be time consuming or difficult.

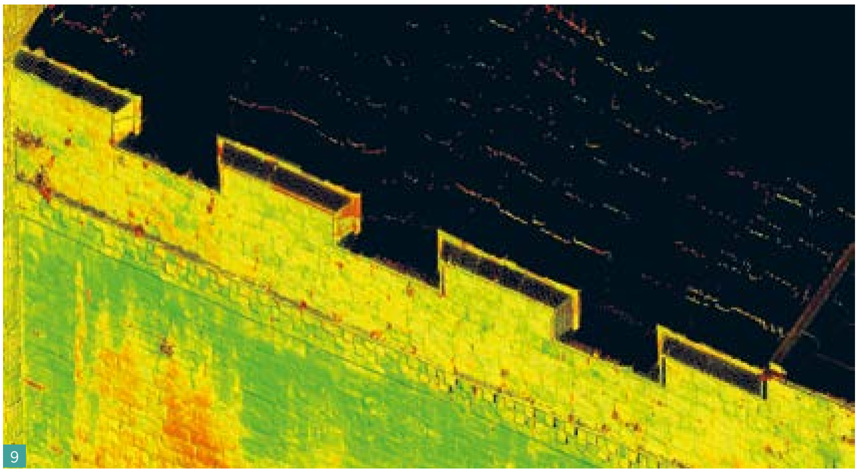

Fig. 9 Laser scan data showing Mixed Pixel noise trailing the edges of the wall parapet.

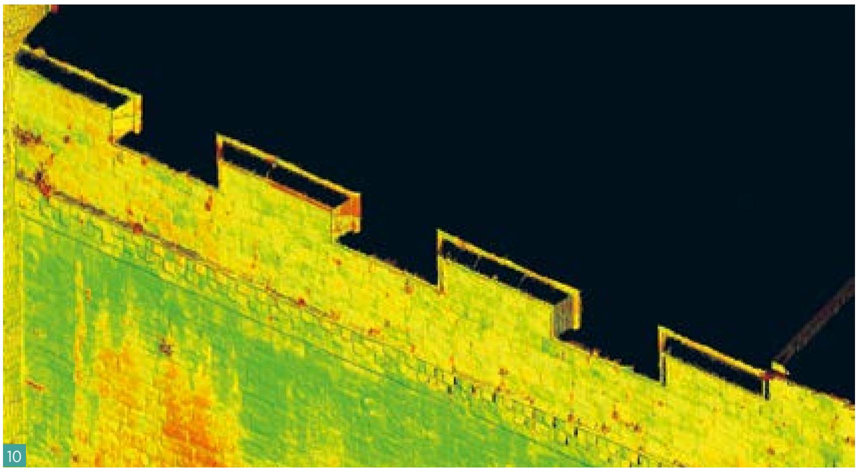

Fig. 10 Laser scan data with Mixed Pixel filter applied to remove noise.

2.7.10. Registration

Individual scans record the environment around the scanner, with the nodal point of the scanner as the centre point for the local coordinate system (i.e. XYZ coordinates of 0,0,0). To join separate scans together, they must first be 'registered' to align the scans in the same coordinate system accurately. This process transforms one or more scans around a fixed scan using translation and rotation, typically improving alignment via best-fit algorithms.

The alignment is commonly achieved using targets or by identifying overlapping data points, often referred to as 'feature based' or 'cloud to cloud' registration. Some automatic registration algorithms exist to automate this process, though currently these have limited application and are largely dependent on the type of site for favourable conditions. The software used for registration should provide a statistical report and metadata with key information describing the accuracy of the alignment.

2.7.11. File formats

TLS data can be stored in a gridded or ungridded style. Gridded data uses a spherical grid to record the lines of data as rows and columns typically enumerated in the file header. Some file types such as .PTX and .E57 can preserve this information in registered datasets. Ungridded data simply stores the points with XYZ coordinates (and like gridded data, any additional point data such as RGB). Data cannot be trivially converted from ungridded to gridded formats.

Another major distinction for file formats is the storage of the data in ASCII or Binary. ASCII formats are effectively readable via a text editor, and the data points can be distinguished or even edited. These formats often have the largest file sizes as it is an inefficient way of storing the data, though they may be best for archival purposes or use in other software. Binary formats require comparatively far less storage capacity though may be unsupported by different softwares and are typically, with the exception of ASTM's open-standard E57 format, unsuitable for archival use.

2.8. Photogrammetry

Photogrammetry is a broad body of techniques that use photography to derive 3D information based on differences between lines of sight of the same subject (known as parallax) in two or more images. Its development has over a century of history, though recent developments in computer vision and computational hardware has led to the development of 'Structure from Motion' (SfM) photogrammetry, which has rapidly become a widely adopted and powerful technique for producing potentially highly accurate 3D datasets. It functions by simultaneously reconstructing scene geometry and camera position and orientation in a bundle adjustment operation using a set of features derived from overlapping input images. Whereas previous photogrammetric techniques required a calibrated camera and lens setup with known parameters, these can now be calculated automatically during the alignment.

2.8.1. Photography

The quality of the photographs taken during the data capture process determines the quality of the model or point cloud produced via SfM, and follows broadly similar rules to traditional photography. The principle of 'Garbage in Garbage Out' applies strongly, and poor images will result in a low quality 3D dataset. The following criteria should provide a rule of thumb for capturing suitable images:

- The subject is in focus (use a high aperture such as f/16+ to expand the depth of field, though be aware that too high, e.g. f/32 will introduce blur from diffraction)
- Motion blur is minimal (camera shake can be eliminated with a tripod and remote shutter release)
- The exposure is balanced and metered for the subject (rather than the extraneous environment or sky), using the lowest ISO (sensor sensitivity) available
- Lighting should be neutral and diffuse (undertake outdoors capture on overcast days; use artificial lighting to control light)
- Ensure adequate overlap and common features between images to align (a minimum of 60% is a rough guide; use targets on flat, featureless surfaces)
- Aim for consistency between images, i.e. lock white-balance, exposure, focal length
- Greater numbers of photographs from varied angles will improve the relative accuracy
- Use large sensor cameras with high quality lenses for greater dynamic range, lower noise and higher resolution imagery (fixed focal length/prime lenses are ideal)
- Capture in RAW format (other formats such as JPEG or TIFF can be generated from this)

Due to the low price and wide availability of high-capacity digital storage such as flash cards, users are encouraged to take a generous number of photographs through the course of a capture session or survey.

2.8.2. Capture methodology

Using SfM for site-scale capture involves thoroughly capturing all accessible and visible surfaces from the greatest number of unique angles. In practical terms, taking photographs aimed at the subject from near-ground level, standing height and, from an elevated position, should give stronger vertical coverage. Repeating this incrementally at offset around the perimeter of the surfaces should give an even overall coverage, per Fig. 11.

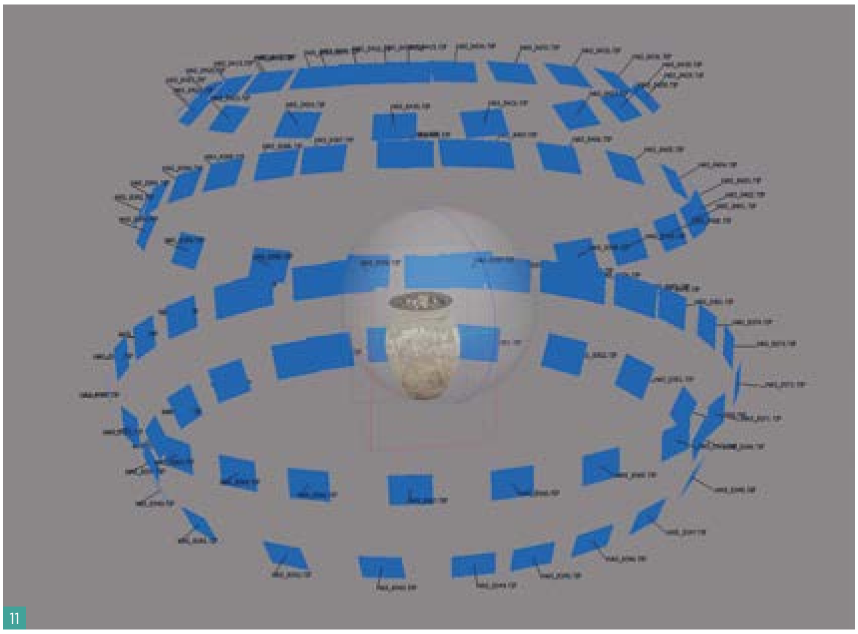

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Fig. 11 Aligned camera positions shown relative to 3D model produced via SfM.

With laser scanning, the achievable point-to-point resolution of a surface at a distance is typically defined by the scanner. However, with photogrammetry this is defined by the measurable real-world distance between image pixels, known as the Ground Sample Distance (GSD). This can be calculated using the following formula (listed in the Historic England Metric Survey Specification, 2015):

$\mathrm{GSD} = (H/f) \times p$

H = distance between camera and subject

f = focal length

p = pixel size (sensor size on one axis / pixel count on same axis)

The GSD can also be calculated from an image that features a scale or known distance by simply dividing the exact number of pixels occupied by the scale or known point of reference. For example, if a 1000mm scale bar occupies 2000px (pixels) of an image, the GSD is 0.5mm.

2.8.3. Scaling and control

Unlike other digital documentation techniques such as laser scanning, photogrammetry is not inherently scaled or measureable. The specification of the project might not require measureable dataset, which could be the case for visualisation or interpretive purposes. However, if the data is for applications that require measurement, say for conservation monitoring, it should be scaled using a reference contained within the source photography (such as Fig. 12). This should be included in the survey design, and could be as simple as including a scale bar or ruler in shot preferably in several images. The scale bar is later identified during processing and assigned a known value, e.g. 30cm. Using an engineering calibrated rule will ensure the most accurate scaling in this instance.

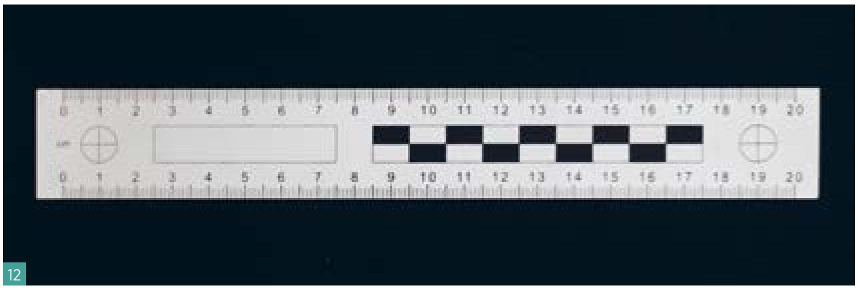

Fig. 12 Example of a scale bar.

Setups that are more sophisticated might use a series of targets placed throughout the site or around the object that are captured via Total Station (or laser scanning) and later matched to the produced XYZ coordinates. This will result in scaling the photogrammetry data and placing it on the site coordinate system.

2.8.4. Processing workflow

Whilst different SfM photogrammetry software will likely use varied terminology, the same general workflows apply for processing photographs into 3D content.

1. Pre-processing images such as raw conversion and exposure adjustment
2. Loading in and/or selection of images from the overall dataset
3. Masking images to remove extraneous input data (this may precede step 2 if done externally)
4. Alignment of photographs using common features; generation of a ‘sparse’ or feature alignment point cloud
5. Optimisations and adjustments to camera alignment
6. Scaling using markers (optional)
7. Depth calculation and the creation of a dense point cloud
8. Editing and cleaning the dense point cloud (this itself may be an output)
9. Meshing dense point cloud into a 3D model
10. Editing and refinement of model
11. Photo-texturing the model

Many of these steps are computationally intensive operations on the system CPU (Central Processing Unit) and GPU (Graphics Processing Unit) whilst using large amounts of system memory. For larger projects processed to a high specification, high-end systems are required to achieve these workflows in a useful timeframe. Some services provide cloud-based processing to transfer this workload from the user to a remote server.

2.8.5. Photo texture

In addition to 3D spatial data in the form of a point cloud or model, SfM enables the creation of texture maps of the surface using the input images, depicting colour and surface details that may not be well represented in the geometry. The position of each aligned photograph determines the area of texture that will be derived from the image, with most software packages further blending between images to provide an even exposure. Fig. 13 shows textured and untextured views of the same 3D object produced via SfM; note how reconstructed areas of the artefact are more clearly identifiable in the textured model.


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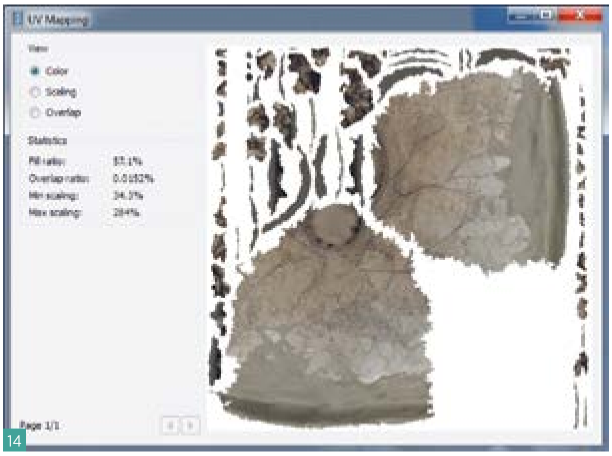
Fig. 13 3D model of artefact shown in textured (left) and untextured (right) rendered views.

The mapping process is largely automated and will require input parameters such as target resolution, which defines the dimensions of the output texture map size. If this is too low, the final texture will not resolve details well; too high, and the texture map may be unusable and needlessly exceed the resolution of the input images themselves. During the mapping, the model is 'unwrapped', which is a projection of the 3D model onto a 2D plane. To reduce distortion from the projection, contiguous areas with similar topology will be grouped into clusters. The projected areas are mapped using UVW coordinates that connect the 2D clusters to the 3D model. Texture maps with fewer clusters will generally use the specified resolution more efficiently though may show more distortion. Those with more clusters may require a larger map size to resolve the same details. Fig. 14 shows an unwrapped UV map for a 3D model produced via photogrammetry, with statistics relating to the efficiency of the completed unwrap.



Fill ratio: 57.1%
Overlap ratio: 0.0182%
Min scaling: 34.3%
Max scaling: 284%

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Fig. 14 Unwrapped texture map created by SfM photogrammetry. The statistics show how efficiently the photo-textures from the 3D model unwrap to occupy the 2D planar space.

2.8.6. Limitations of photogrammetry

Photogrammetry is an optical system, like terrestrial laser scanning, meaning the quality of the dataset is highly dependent on the subject and the environment. Materials that are: highly reflective; glossy; light absorbent (low albedo); refractive or scattering, pose problems for capture. These can be mitigated to some extent through the use of highly diffuse lighting and polarisation filtering techniques to remove reflection. Surfaces with few features, such as a plain painted wall or large area of smooth ceramic may also have problems aligning. This can be remedied by using fixed targets or projecting a static pattern onto the surface.

In addition to inclement weather conditions such as fog, rain or snow, another consideration for outdoor photogrammetry is lighting. Strong sunlight can create hard shadows and bright reflections from high albedo surfaces; this increases the difficulty of achieving a well exposed photograph. Boosting the shadows later on a poorly exposed photograph will only further introduce noise and thus lower the accuracy of the reconstructed 3D scene. In addition, the lighting conditions will effectively be ‘baked in’ to the texture of the model, which may preclude relighting the model.

2.8.7. File formats

Projects using photogrammetry will generate data at three main stages: the raw photographic data during capture, the processing project data (typically a proprietary format of the app or software package) and deliverables created through processing, such as 3D models or point clouds.

Input data should be stored as camera raw (such as DNG – Digital Negative), and any derivate files produced from this such as edited images as lossless (TIFF or PNG). Using images with lossy compression will introduce additional noise into the model, reduce the accuracy of the reconstruction, and lower the quality of the photo-texture.

It is advisable to retain the project files, which are often fairly efficient in size, as this can allow reprocessing and editing of the generated assets. These are typically proprietary formats that are incompatible with other software.

Outputs from photogrammetry are primarily dense 3D point clouds, meshes or orthoimages (orthographically rendered images, often used for building elevations or aerial imagery). Point clouds share similar formats to terrestrial laser scanning. Orthoimages are typically TIFF format and may be accompanied by a sidecar metadata file containing scaling information. A range of formats exist for 3D meshes and models, though the most common are OBJ (an open format) and FBX (proprietary format). Depending on the format, associated textures and material information will be either externally referenced in the file system via a metadata file, or integrated into the 3D file.

2.9. Mixed datasets

Combining datasets from different sources or capture instruments is often necessary for the purposes of acquiring a greater degree of site coverage. It can also be useful in overcoming limited physical access or to facilitate a safe system of work. Other uses might include transforming SfM data relative to measured data such as ground-control points captured via total or multi-station, or to laser scan data to augment photo-textures. Spatial datasets should already be compatible if two or more sources are consistently scaled and correctly located within an identical coordinate system. If the two datasets are not located or scaled consistently relative to each other, a transformation will be required to combine the two. This can be achieved either by using control points common to both datasets, or by capturing and identifying overlap from common features appearing in both.

As part of a project to digitally document the 19th century cast-iron Ross Fountain in Edinburgh's Princes St Gardens, a combination of terrestrial laser scanning and SfM was used to achieve greater coverage. Scans undertaken radially around the fountain were spaced at different distances to maximise vertical coverage with a standard tripod (Fig. 15) and a high-elevation tripod.


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Fig. 15 Terrestrial laser scanning at Ross Fountain, Edinburgh. This data was supplemented with additional data captured via SfM photogrammetry.

Due to the height of the fountain and the occlusion of the concave upper bowls, a remotely operated DSLR mounted on a 5m extending pole was used to capture photography for SfM. Several full rotations of the fountain were recorded with photography including close-range high angle images of the upper bowls. This aided the registration alignment between the SfM and laser scanning data, shown in Fig. 16.

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Fig. 16 Preview of alignment between terrestrial laser scanning data and SfM of Ross Fountain, Edinburgh. Scan setups are indicated with yellow-outlined cubes, photographs by white-outlined pyramids showing camera orientation.

The resultant dataset was a more complete representation of the highly ornate fountain that offered greater use for a range of purposes. Furthermore the thickness of the upper cast iron bowl structure could be determined through the combined dataset, which would be used as part of the project to aid the ongoing conservation and restoration of the fountain. A high-resolution meshed version of the dataset was produced for visualisation and obtaining discrete measurements (Fig. 17).

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Fig. 17 Untextured high-resolution 3D mesh of Ross fountain.

2.10. Mobile data capture and remote sensing

There are a number of tools available to record and examine large-scale landscapes, useful in documenting both natural and cultural heritage sites. These methods are better suited to sites that span several kilometres, potentially with tree canopy cover or inaccessible terrain such as water. There are two broad categories: mobile data capture, and remote sensing. Mobile methods include handheld instruments and vehicle mounted scanners, which can employ specially conFigd terrestrial scanners. Remote sensing generally refers to aerial (e.g. drone or aircraft) or satellite data capture techniques.

As these techniques operate on a much wider scale, there is generally more emphasis on geo-referencing the data to national or international coordinate systems. Within the UK, the processed data will often sit on the Ordnance Survey National Grid. It is important to be aware of any transformations that have been applied to the raw data for further use. Combining and moving between datasets that are transformed with a scale factor (as discussed earlier in section 2.6) impacts overall accuracy to a much greater degree with large sites.

For further information on remote sensing, see the International Society for Photogrammetry and Remote Sensing (*www.isprs.org*), which maintains leading journals, publications and hosts international conferences.

2.10.1. Vehicle based scanning systems

Mobile scanning systems work by capturing spatial data whilst the instrument moves through an environment, relying on data captured by a host of sensors to track the spatial relationship between instrument and captured surfaces. A typical setup may use a terrestrial laser scanner in a custom 'profiler' mode or a bespoke profiler, capturing a fixed profile of surfaces in a radius around the instrument. As the vehicle moves through the environment, the series of profiles builds up the database incrementally. Position and orientation tracking is achieved with GNSS and an Inertial Measurement Unit (IMU), and may also use further information from the vehicle such as an odometer. GNSS allows this dataset to be converted from WGS84/ETRS89 to national coordinate systems or a local grid.

For the Forth Bridges digital documentation project in Edinburgh, data acquired via mobile capture systems was used to supplement terrestrial laser scan data. Using a Leica Geosystems' Pegasus boat-mounted profiler system shown in Fig. 18, otherwise inaccessible areas under and surrounding the Forth Bridge and Forth Road Bridge could be captured. Likewise, the Pegasus car-mounted profiler shown in Fig. 19 enabled the capture of the surrounding road systems and four lanes of the Forth Road Bridge deck level. The mobile system allowed more complete and consistent coverage for these areas, a safer working environment and did not require road closures during the survey.

Fig. 18 Leica Geosystems Pegasus boat mounted laser profiler.

Fig. 19 Leica Geosystems Pegasus car mounted laser profiler.


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2.10.2. Simultaneous Localisation and Mapping (SLAM)

Systems that can track the moving instrument whilst recording the environment can be used for real-time capture and computer vision based navigation and rapid survey of large scale environments. These systems are referred to as Simultaneous Localisation and Mapping (SLAM) and employ algorithmic solutions to solve environmental and instrument position based on a range of data captured by the system’s Inertial Measurement Unit (IMU) in addition to the spatial scan data. A number of systems exist that are designed for handheld or pedestrian use, allowing users to capture sites by walking around in a systematic approach to maximise coverage (Fig. 20). A range of systems exist at both high-end and lower-end performance and price points; often the trade-off may relate to the resolution and/or tolerances of the instrument. Users should observe the stated specifications to ensure that they meet requirements. Absolute accuracy tolerances are typically in the order of 10-500mm, depending on the hardware, quality of the input data and travel paths.

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Fig. 20 Undertaking data capture on-site via SLAM with the Zeb-Revo. Image courtesy of Historic England.

The following case study was contributed by Historic England and discusses the use and integration of handheld SLAM acquired data with terrestrial scanning techniques to record Belsay Castle historic site in Northumberland.

2.10.3. SLAM data capture at Belsay Castle

The Zeb-Revo consists of a 2D line scanner mounted on a motorised drive. The rotation of the scanner provides the third dimension as the user walks around. There is also an inertial measurement unit which records the motion of the scanner. This combined with the application of a simultaneous localisation and mapping (SLAM) algorithm in the post processing phase, results in a 3D point cloud with a stated range noise of ±30mm at 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 a 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. The scanner has a very basic user interface so it is not until the data is processed that the results are visible. In later versions of the software (3.1.1 onwards) it is possible to adjust the parameters of the SLAM algorithm to ameliorate any problems with alignment.

The Zeb-Revo was used to help complete plans of the tower of Belsay Castle that had mostly been generated from static laser scan data (Fig. 21). The noise in the scans meant that some of the detail of the mouldings was not discernible, but it was possible to use the point clouds to reference scanned images of a previous hand-measured survey to enable the completion of this detail. The level of noise in the Zeb-Revo scans probably means they are not suitable for the production of 1:50 scale plans. Where the scanner comes into its own is for the production of smaller scale plans such as those required for interpretation, for facilities management purposes, or for circumstances in which the use of a static scanner is not possible given other constraints.


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Fig. 21 Cross-section of spiral staircase from Belsay Castle, Northumberland. Data captured with the Zeb-Revo. Image courtesy of Historic England.

2.10.4. Airborne LiDAR

Airborne LiDAR allows the capture of wide landscape scale data and the ability to filter out buildings and tree canopy cover from the collected dataset. In a typical setup, laser scanning instruments are mounted on aircraft which fly over the specified areas, capturing swathes of land (typically between 200-2000m depending on altitude and the system). The resolution of the data can vary, but typical point-spacing often ranges between 25mm and 50mm depending on capture specification. Unlike terrestrial capture the laser beam width or footprint is much greater, typically around 20-300mm depending on altitude and the system. This large footprint increases the likelihood of the laser pulse reaching to ground level through vegetation and tree cover. To extract or remove foliage from the dataset, the waveform of the laser pulse is analysed to find the intensity peak associated with the last return, filtering out the (likely) multiple other reflections from branches, etc.

Processed spatial datasets can be used to produce Digital Elevation Models (DEM) or Digital Surface Models (DSM). During the scanning, most systems are outfitted to capture photographic imagery and orthorectify it. This is useful independently and can be overlaid on the DEM to produce a textured 3D representation of the landscape.

The Centre for Digital Documentation and Visualisation LLP (CDDV) has employed aerial LiDAR for a range of projects to capture significant cultural and natural landscapes, including the St Kilda archipelago (Fig. 22) and the Antonine Wall in Scotland. St Kilda is both a UNESCO Natural and Cultural World Heritage Site, and was digitally documented in tandem with terrestrial methods as part of the Scottish Ten project to create the most accurate and highest resolution record of the site to date. Orthorectified aerial imagery was captured in the process.

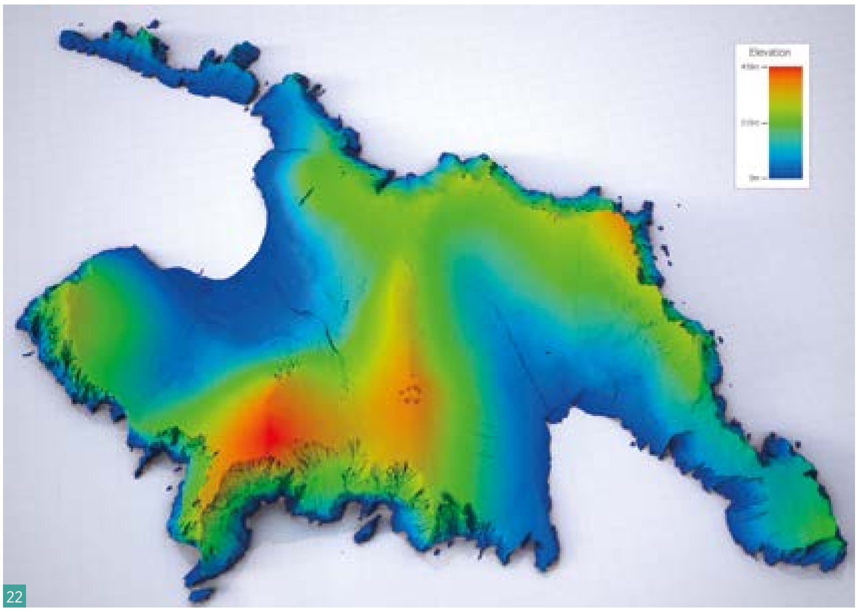

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Fig. 22 Rendered mesh of the St Kilda aerial LiDAR data displayed with an elevation gradient.

The Antonine Wall, a Cultural World Heritage Site, was similarly documented via a range of methods, with specific sites such as the forts at Rough Castle and Bar Hill additionally captured at higher resolution with terrestrial scanning. The majority of the wall itself is earthworks such as banks and ditches, which are also forested in places and thus well suited to be captured with aerial LiDAR. The spatial and photographic data spans over 130 separate kilometre grid squares on the OS National Grid. This data is used as a research resource to further knowledge on the Antonine Wall and for management purposes. Fig. 23 shows a swath of data from the Antonine Wall rendered with a 'hillshade' representation, highlighting the features of the topography with an artificial light.

Fig. 23 Single direction hillshade view of the Antonine Wall aerial LiDAR data, showing Bar Hill fort (centre-left) and the surrounding landscape. Image courtesy of Nick Hannon.

For further reading on the use, presentation and interpretation of aerial datasets, see Historic England's (2010) 'The Light Fantastic'. Also see Kokalj and Hesse's (2017) monograph 'Airborne laser scanning raster data visualisation'.

2.10.5. Satellite and multispectral imagery

Satellites designed for imaging are a global remote sensing technique that capture and assemble multispectral imagery of swathes of land within the orbit of the craft. Unlike typical 3-band (RGB) photography, most satellite sensors are multispectral and produce datasets that include additional infrared bands. These additional bands can provide further information about the surface captured, identifying otherwise hidden features, helping to 'classify' areas (e.g. as urban, water or vegetation) and even showing emitted thermal radiation. Some systems capture hyperspectral imagery, which operates similarly but greatly expands the number of collected bands, for instance over 200 separate but narrower bands (each at 5-10nm). This additional data allows significantly more detailed analysis of captured areas, creating a spectral signature for individual pixels that can accurately classify areas such as by specific minerals in soil and vegetation type.

The resolution of satellite imagery available has been a function of both the resolution of the capture instrument (sensor and optical system) and legal requirements. Commercial sale and use of satellite imagery beyond 500mm GSD was deregulated in the US in 2014, with current commercial satellites in-orbit capable of capturing data at 310mm at the time of writing. This impacts both the level of detail visible in the 2D imagery, but also the resolution of derivatives such as Digital Elevation Models generated through photogrammetric processing of the captured imagery. These datasets can be used for a range of purposes on a global scale, including documenting unknown and potential cultural heritage sites. When captured regularly over a period of time the data can be used to monitor changes to the natural or built environment, identifying issues affecting the conservation of heritage sites such as urban encroachment and destruction of sites.

2.10.6. Interferometric Synthetic Aperture Radar (InSAR)

Synthetic Aperture Radar (SAR) is a form of radar imaging that is typically used from aircraft or spacecraft and captures multidimensional information about a swathe of land within the flight path. The emitted radio waves reflect off the surface and are received by the instrument, enabling the calculation of distance based on time elapsed and surface properties based on attributes of the signal (e.g. intensity). The distance resolution depends on the pulse length, achieving in the order of millimetres to centimetres according to the application. One of the strengths of radar based techniques is that they are largely unaffected by weather, whereas heavy fog, cloud cover or pollution smog will inhibit optical techniques.

As the craft moves along its path, it captures swathes of the target area to assemble into an image. The azimuth resolution is defined by the beamwidth, and in real aperture radars this is a function of antenna length and wavelength. SAR improves the azimuth resolution of this technique by synthesising a very large aperture through combining echoes along the flight track. In addition, frequency modulation can be used to further improve azimuth resolution and improve ranging resolution through inducing modulation in the signal.

Interferometric SAR (InSAR) enables measurement of the radiation travel path and can be used to monitor displacements or movement between two or more epochs in the surveyed areas. It is regularly employed to assess seismic or volcanic activity, as it allows differences in the order of centimetres to be mapped. It can also be used to generate Digital Elevation Models of a landscape, which is typically in conjunction with control data such as GNSS ground points.

2.11. Close-range capture techniques

Digital documentation of objects and artefacts uses techniques that operate at higher tolerances and resolutions than typical site-scale data capture. These are generally applied in situations where fine-grained spatial and photo-texture information is required to digitally represent the object, and examples vary from the very small (e.g. archaeological artefacts <20mm) to significant areas (e.g. inscribed stones >1000mm). Typical capture distances between the scanner and the object are 100-1000mm, depending on the technique and the scale of the object.

The techniques discussed are non-contact optical systems, enabling the capture of fragile objects that may require specialist handling and access. As optical systems, they often exhibit similar limitations as site-scale scanning techniques, such as difficulties when capturing reflective, refractive and scatting materials. The datasets can be used for a range of applications (discussed further in section 3), including for example virtual access to artefacts that may be in a museum collection, on display behind glass or in storage.

2.11.1. Triangulation laser scanning

The principle of triangulation laser scanning uses the known offset and angle between a laser emitter and the sensor to calculate the spatial position of the light on the object surface. Scanning with this method typically captures a swathe of data before the scanner or object must be moved to capture further data. Depending on the scanning hardware used, these swathes may need to be registered together using common surface features or targets. Fig. 24 shows an arm-mounted laser scanning system that captures data along a profile in synchronisation with the position of the arm. The profile data is then translated into a common coordinate system to assemble a dataset of the surface or object.


24

Fig. 24 Arm-mounted triangulated laser scanner being used to capture runic inscriptions at Maeshowe Neolithic chambered tomb in Orkney.

Different systems can capture data in larger swathes, typically via static tripod mounted scanners as per Fig. 25. The swathes of data are registered together into a common coordinate system using overlap between the captured areas.

25

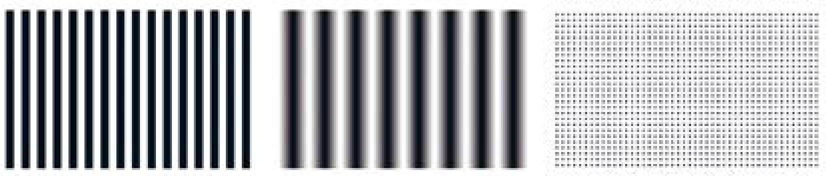
Fig. 25 Konica Minolta VIVID 9i used to scan Dunadd's ogham inscribed stone in Argyll.

Typical accuracy tolerances are around 0.025mm to 0.05mm though the capture resolution may be lower.

File formats are typically point cloud and mesh. Some systems use the camera to acquire RGB imagery to photo-texture the mesh.

2.11.2. Structured light scanning

Structured light scanning records surface geometry through measuring distortion of a projected light pattern (typically white light or infrared) from a projected source. The camera detects the pattern and software uses this information with the known camera-projector offset to triangulate the pattern to produce measureable data. Some systems use a fixed projector-camera offset setup and project static patterns, whilst others may allow readjustment of the offset and the projection of variable patterns to better resolve surface details. Fig. 26 shows several common types of patterns typically employed by structured light scanners.



26

Fig. 26 Examples of common structured light patterns. From left to right: high frequency stripes; sinusoidal; dot-grid.

Capture methodologies vary between setups with static capture of swathes of data, and mobile capture with an actively moving scanner or subject. Systems that project sequential patterns typically require a static subject, whilst others that use fixed patterns can capture at a relatively high rate of frames per second (fps). This enables the rapid capture of complex surfaces and entire objects with a preview of the captured dataset, as shown in Fig. 27.

Fig. 27 Structured light scanning using an Artec EVA.

File formats are typically point cloud and mesh. Many systems use the camera to acquire RGB imagery to photo-texture the mesh.

2.11.3. Reflectance Transformation Imaging (RTI)

Reflectance Transformation Imaging (RTI) differs from the other spatial capture methodologies as it does not capture 3D data; rather it generates a ‘relightable’ image that can also be viewed with different shaders to enhance and reveal surface information. This is achieved through capturing a series of photographs from a fixed camera position with the subject lit by a light source incrementally moved around points on a hemispherical grid. These photographs are used in conjunction with the known light position relative to the camera to calculate the surface normals per pixel for the captured surface. The quality of the results depend largely on how many light positions were captured and how well distributed they are. The subject must be in focus and remain static, and better camera hardware such as large sensor size and high quality lens optics will ensure higher resolution and sharper images.

2.11.4. RTI dome methodology

One method for undertaking RTI data capture is through the use of a dome framework with a fixed multi-light setup connected to a microcontroller (Fig. 28). The dome method uses an array of lights with known positions prior to undertaking data capture, with the camera at the zenith of the dome, as shown in Fig. 29. These lights are activated sequentially and the object is captured lit from different angles in separate photographs. Due to the size of the dome and the complexity of the setup, the dome method is preferable for a repeatable studio setup.


28

Fig. 28 Framework for geodesic RTI dome using 65 LED lights. Image courtesy of Kirk Martinez, University of Southampton.

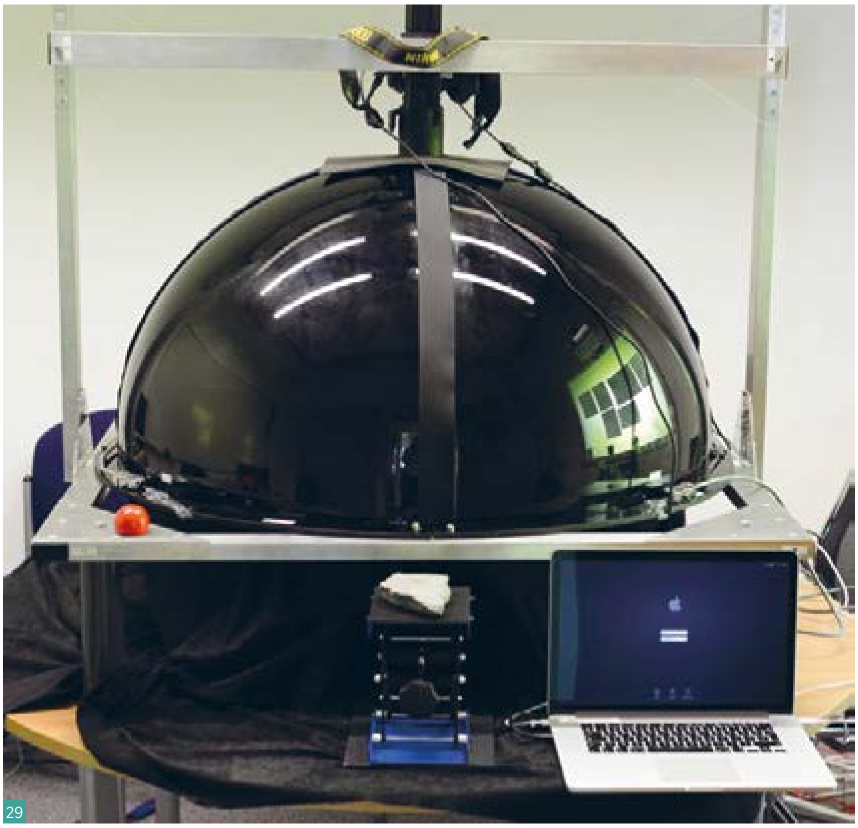

29

Fig. 29 Finished RTI drone assembly with camera (top) and vacuum formed plastic dome to shield ambient light. Image courtesy of Kirk Martinez, University of Southampton.

The second method lends itself to situations where mobility is important, as the setup is lightweight and can be easily adapted for fieldwork, for example capturing carved stone surfaces in-situ. This method for undertaking RTI is with a single light source (e.g. a camera flash or 'strobe') with a small black or red reflective sphere placed in shot, as shown in Fig. 30. A sequence of images is captured with the strobe in the next position on the grid, ensuring the camera remains static. Capturing images outdoors may require the use of umbrellas or an awning to reduce light levels, whilst also slightly underexposing photographs. Correct use of the technique should not overexpose the surface and the strobe's highlight should be clearly visible on the sphere.

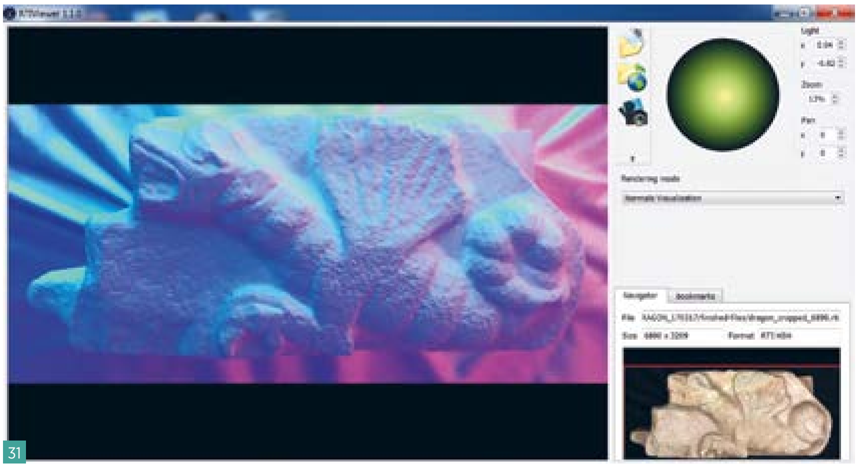

30

Fig. 30 RTI capture of a carved stone object.

2.11.5. Processing RTI and outputs

The processing workflow for the second method of RTI firstly requires the software to reconstruct the light positions. This is by using the reflective sphere to capture the reflection highlight of the moving light. Computer vision algorithms detect highlight positions and the edge of the sphere, calculating light source locations based on their highlight position on the spherical surface.

To generate surface information for the subject based on these input images, a ‘fitting’ algorithm is then used to produce a reflectance function per image pixel based on surface normals (Fig. 31). The relightable image datasets are produced as either .RTI or .PTM formats, depending on the fitting algorithm used. Specific viewers are available for the output files, such as that shown in Fig. 32.



31

Fig. 31 RTI generated normal map.

32

Fig. 32 RTI dataset visualised with specular enhancement shader.

A typical processing workflow is as follows:

1. Collect the input photographs into a directory
2. Pre-process photographs in image editing software if necessary, such as for colour correction
3. Create the project in the RTI builder software
4. Choose a fitting algorithm and define the capture method (e.g. highlights on a reflective ball)
5. Supervise the highlight detection to identify the light positions
6. Define the required area/dimensions for the intended output file
7. Generate the RTI or PTM file

Further details of workflows and access to open source RTI software is available from Cultural Heritage Imaging (*www.culturalheritageimaging.org*).

2.11.6. Turntable SfM photogrammetry

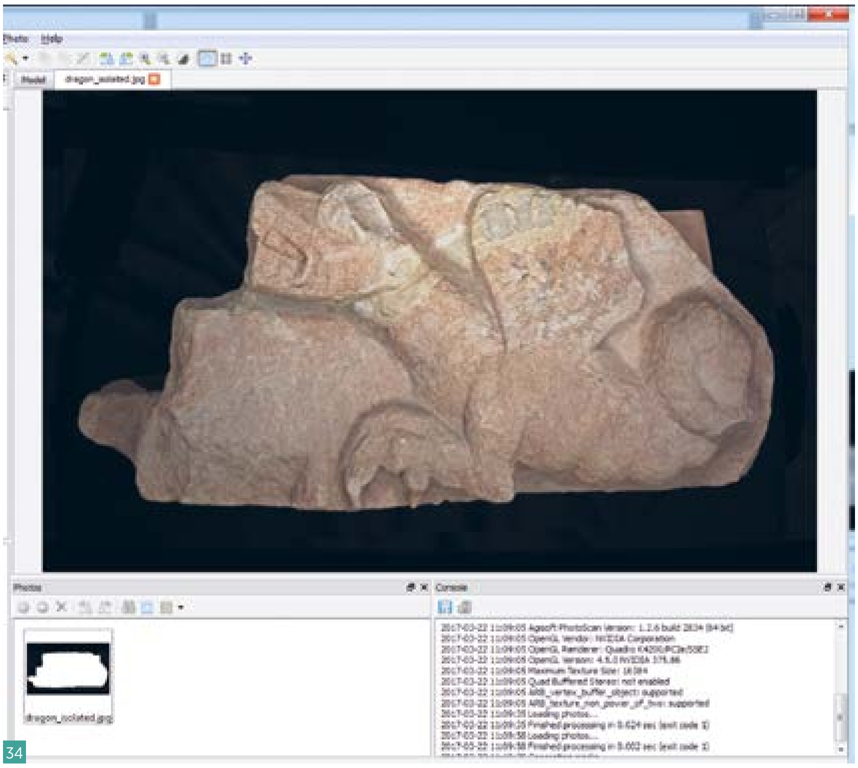
Close range capture of objects with SfM operates with the same principles as site-scale capture. However, it is also viable to move the object so long as it is isolated (e.g. using 'masks') from its static background. This method is used in a turntable setup, with the object on a pivoting turntable and the camera typically fixed on a tripod. Using this approach can be highly efficient and allows controlled, repeatable capture of objects. The main limitation is that the object must be small enough to use in the turntable setup, and able to be handled.

Controlling the lighting is one of the most important considerations for photogrammetric data capture. In a turntable setup, using photographic tools such as softboxes and diffuse studio lights will help to provide an overall diffuse light and aim to reduce specular reflections. See Fig. 33 for an example of a turntable setup with lighting.


33

Fig. 33 Photograph of an example photogrammetry setup. The softbox can be used to diffuse and block uncontrolled light.

In this setup, the object moves whilst the background remains static, so the photogrammetry software must be instructed to ignore the background or it will attempt to align images despite the inconsistencies. To isolate the object from its background, the physical setup should aim to use a single colour that can be identified later and ignored using a 'mask'. Setups might use a black velvet style backdrop which extends to cover the floor and turntable, returning the lowest amount of light possible, as shown in Fig. 34. Alternatively, any solid colour backdrop could equally be used to achieve background isolation. The object's material and how it is best separated through contrast should govern this choice. Masking can also be manually defined and edited, though it is laborious and undermines the efficiency of using a turntable setup.



34

Fig. 34 Black backdrop photograph, processed in image editing software to threshold out black background. Shown with mask in bottom pane.

Some objects may prove difficult for SfM alignment due to the nature of surface material or details; placing targets around the object can improve tracking, though these should be removed from the final point cloud or mesh model.

3. APPLICATIONS OF DIGITAL DOCUMENTATION

This section will highlight a range of case studies that have applied digital documentation within the cultural heritage environment for different purposes. Key objectives, methodologies and results will be described to introduce the projects as examples for users looking to employ digital documentation methods beyond data capture and recording.

3.1. Conservation

The techniques and methodologies of digital documentation offer a suite of valuable tools for the conservation of sites, monuments and artefacts. Increasing availability of non-contact and non-destructive methods to record cultural heritage has had a significant impact on conservation science, including how professionals work with material and plan conservation strategies. As outlined by the International Council on Monuments and Sites (ICOMOS) in the charter for 'Principles for the Analysis, Conservation and Structural Restoration of Architectural Heritage' (2003), quantitative methods should form a core part of assessment. It emphasises approaches to 'Research and diagnosis' drawing on data to inform plans of activities for multidisciplinary teams. Section 3.7 of the charter also notes that "traditional" versus "innovative" techniques must be "weighed up on a case-by-case basis", and preference should be given to the least invasive approach but also consider the associated risks and safety. It follows that digital documentation is well suited to provide a range of useful data, enabling cross-disciplinary working and offers a foundation to plan further action.

For further reading, Historic Environment Scotland makes available a series of conservation advice documents for built heritage in the form of Short Guides. These can be accessed online or in print via *www.engineshed.org*. The Institute for Historic Building Conservation (IHBC, *www.ihbc.org.uk*) and The Society for the Protection of Ancient Buildings (SPAB, *www.spab.org.uk*) also both provide conservation advice for built heritage, including professional training and CPD.

3.1.1. Digital techniques, conservation science and traditional skills at Paisley Grand Fountain

As part of a scheme of planned conservation works at Paisley Grand Fountain in 2008, the CDDV digitally recorded the fountain prior to disassembly with the aim of visualising alternative paint schemes and providing measured data for potentially for rapid prototyping and to aid casting. The use of digital capture methodologies enabled a unique approach to cast iron restoration of the fountain's structure, serving as an important factor in helping to secure Heritage Lottery Fund (HLF) funding, in addition to HES and Renfrewshire Council support.

The cast-iron fountain was built by the Sun foundry in Glasgow in 1868, stands 8 metres tall and is situated within Paisley's Fountain Gardens. Its state at the time of the survey, shown in Fig. 35, was a deteriorated condition with noticeable signs of oxidation to the cast iron structure, loss of paint and surface detail. The works would remove the corrosion, replace and recast components, where necessary, and return the structure to its original paint scheme.

35

Fig. 35 Paisley Grand Fountain condition at time of survey.

Data capture was undertaken over two days, using a time-of-flight terrestrial laser scanner (Leica Geosystems ScanStation 2) to capture the structure of the fountain. Detailed components were captured with a Perceptron Scanworks triangulated laser scanner. The data was subsequently meshed and used as the basis to create reconstruct a complete 3D model of the fountain for visualisation purposes per its original form. To ensure the accuracy of the model was validated against the captured data, comparative checks were undertaken to map differences between the model and the meshed scan data, shown in Fig. 36 opposite. Expansion and the loss of material from corrosion is also reflected in the deviation gradient.

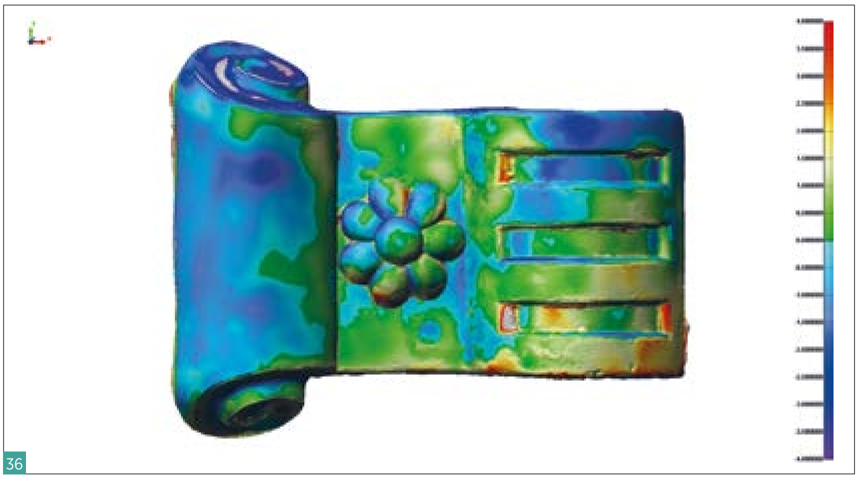

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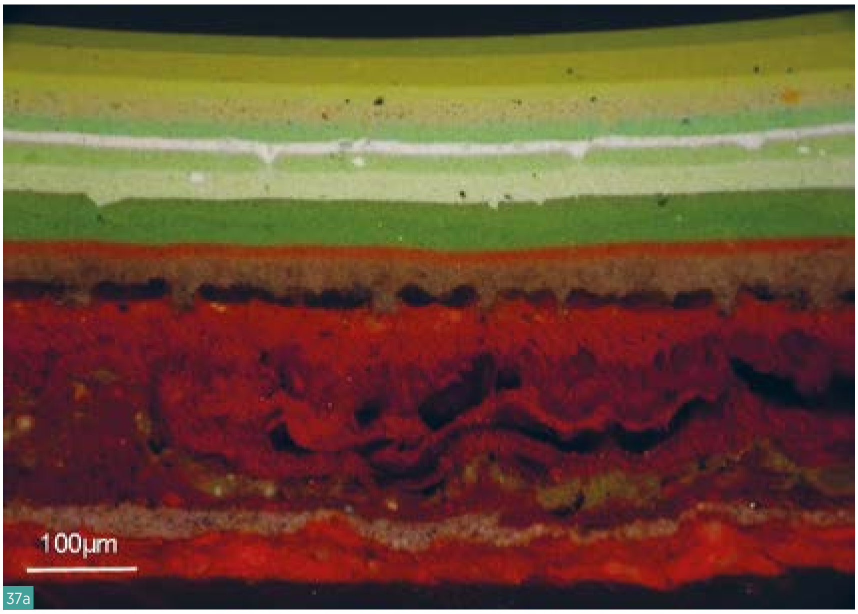
Fig. 36 Deviation map showing extent of difference between laser scan data mesh and modelled component. Red, yellow and green areas correspond to accretion or expansion, blue and purple denote loss or shrinkage.

Paint analysis of the fountain identified many layers corresponding to repainting over its 140 year history, shown in Fig. 37. A reconstruction of a previous colour scheme based on the data was assembled through coordination with conservation specialists and applied to the 3D model. This led to the development of specific material shaders for the intricate scheme and details of the monument, also shown in Fig. 37.



37a


37b

Fig. 37a Section of paint sample taken from Paisley fountain showing paint layers.

Fig. 37b Modelled 3D reconstruction showing one conjectured previous paint scheme based on paint analysis

Findings from the Paisley fountain project identified roles for the captured dataset beyond its use as a record at the time of survey. The potential use of the measured data as part of the casting process was also mooted, with a view to augmenting traditional foundry methods which used layers of built-up plywood as the base for iron casting moulds. With the benefit of accurate data, this offered a more objective and potentially more efficient approach to casting techniques, to improve the overall scheme of conservation. The conserved fountain was reinstated in Paisley in 2014 in as-new condition with a paint scheme derived from the analysis and associated modelling.

3.1.2. Replication of Lurgan fountain

In 2011 an opportunity arose to apply digital documentation techniques to inform the fabrication of a fountain for Mesnes park, Wigan, based on an identical Coalbrookdale 1878 cast iron fountain at Lurgan in Northern Ireland. Deterioration of the fountain at Mesnes led to its removal in the early 20th century, though documentary evidence provides ample basis for the instatement of a reproduction and its paint scheme. The CDDV undertook 3D data capture of the fountain at Lurgan and provided a range of outputs used to support the project.

The measured data from the survey was a key part of the casting and fabrication process, as the component parts were based on dimensions and geometry from the dataset. The fountain was captured with a phase-based terrestrial laser scanner (Leica Geosystems HDS6100) using traditional and high-elevation tripods as shown in Fig. 38. This is supplemented by close-range detailed scanning with a structured light scanner (Artec MHT).

38

Fig. 38 Laser scanning at Lurgan fountain

The 3D data was used to generate a visualisation of the planned replica at Mesnes park through the application of material shaders directly to the processed mesh data. This enabled the creation of a preview of the end product, providing a visual guide to aid decision making. Fig. 39 shows the paint scheme agreed upon for the fountain.

Fig. 39 Render of Lurgan fountain data with previsualised colour scheme.

Measurements from larger components such as the bowls and the main basin torus were generated based on dimensions directly from the laser scan data. To reproduce the detailed sections, the close-range mesh data was processed into manifold geometry for fabrication and used for CNC milling of a polyurethane foam piece for casting (see section 3.3.1). The data for the ornamental cherub fountainhead is shown in Fig. 40, pictured with the iron cast from the rapid prototype. Traditional techniques, as discussed in section 3.1.1, typically use layers of plywood to form the base for a cast, relying on the skills and eye of the sculptor.

Fig. 40a Lurgan cherub data with overlayed contour slices.

Fig. 40b Cast of cherub based on CNC milled foam replica.

Casting and painting of the parts was undertaken at a Wigan foundry, and the fountain was assembled at Mesnes park in summer 2013. The completed reproduction fountain, shown in Fig. 41 is fully operational. The project engaged the strengths of digital documentation, enabling speculative visualisation of the end-product in decision making. Directly drawing from the high-resolution 3D dataset assisted a move towards a more objective method of Coalbrookdale design.

41

Fig. 41 Installation process and completed fountain at Mesnes park, Wigan.

3.1.3. Worn surface analysis of the Stone of Destiny

During temporary relocation from its protective displays at Edinburgh Castle in February 2016, the Stone of Destiny was subject to a rapid scheme of digital documentation to capture a high-resolution record using a range of techniques. This would allow repeat re-evaluation of the stone after it was inaccessible, and provide analytical outputs for stone experts to develop a clearer interpretation of the stone's condition and history.

The primary data capture techniques were via arm-mounted triangulated laser scanner (pictured in Fig. 42), structured light scanner, capturing texture information, and Reflectance Transformation Imaging (RTI) of planar stone faces. This resulted in 3D geometric data at sub-millimetre resolution (Fig. 43) and 2D datasets that could be measured, virtually re-lit and shaded for enhancement to highlight surface detail.


42

Fig. 42 Arm-mounted triangulated laser scanning of the Stone of Destiny.

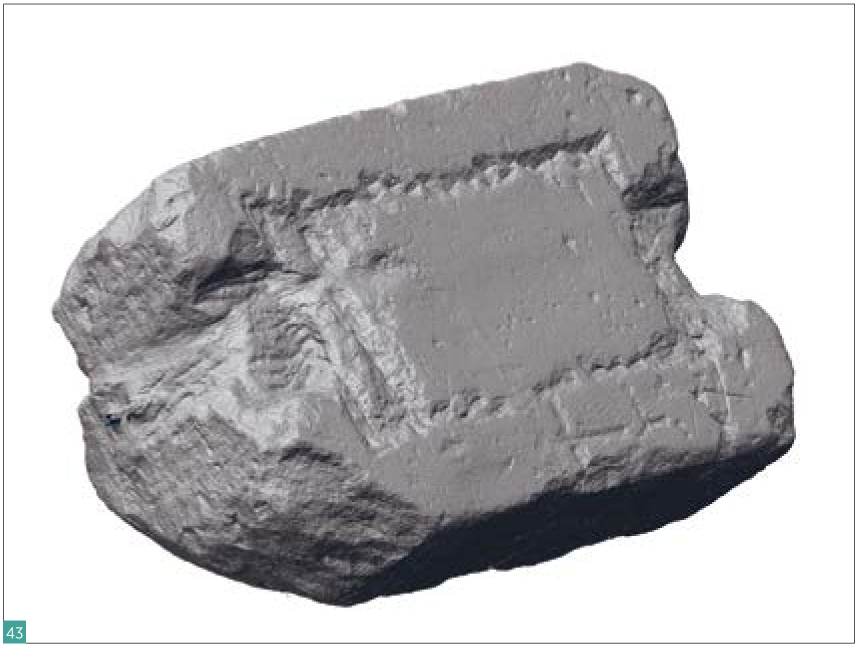

43

Fig. 43 A rendered view of the 3D dataset produced by the triangulated laser scanner visualised with a basic material shader.

Re-evaluation of the stone using the captured datasets allowed further observations to be made about the stone's use and treatment. Worn surfaces, tool marks, the sinking for the rings and signs of later repairs are emphasised and recorded. A subtle longitudinal hollow in the centre of the stone was made clearer in the analysis of the RTI dataset, using the specular enhancement shader (Fig. 44) to create a synthetic raking light. This led to the suggestion that the stone was carried with a wooden bar. The new interpretation information will be presented alongside the stone at its exhibit.

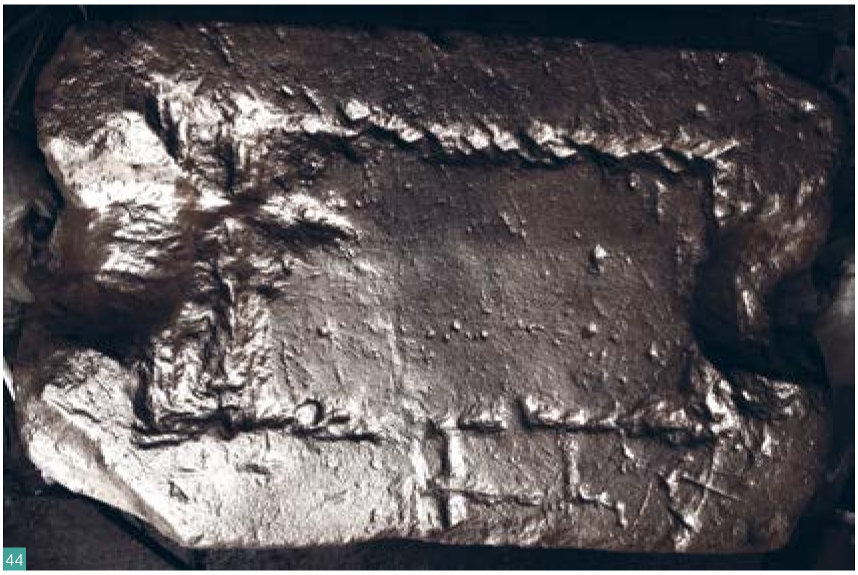


Fig. 44 RTI dataset of the stone of destiny using a specular enhancement shader.

3.1.4. Virtual reassembly

The adoption of digital methods to virtually reconstruct cultural heritage sites and monuments is well established within the field. The tools presented by 3D data capture and visualisation offer archaeologists, conservators and many other specialists a variety of ways to engage with, study and present evidence.

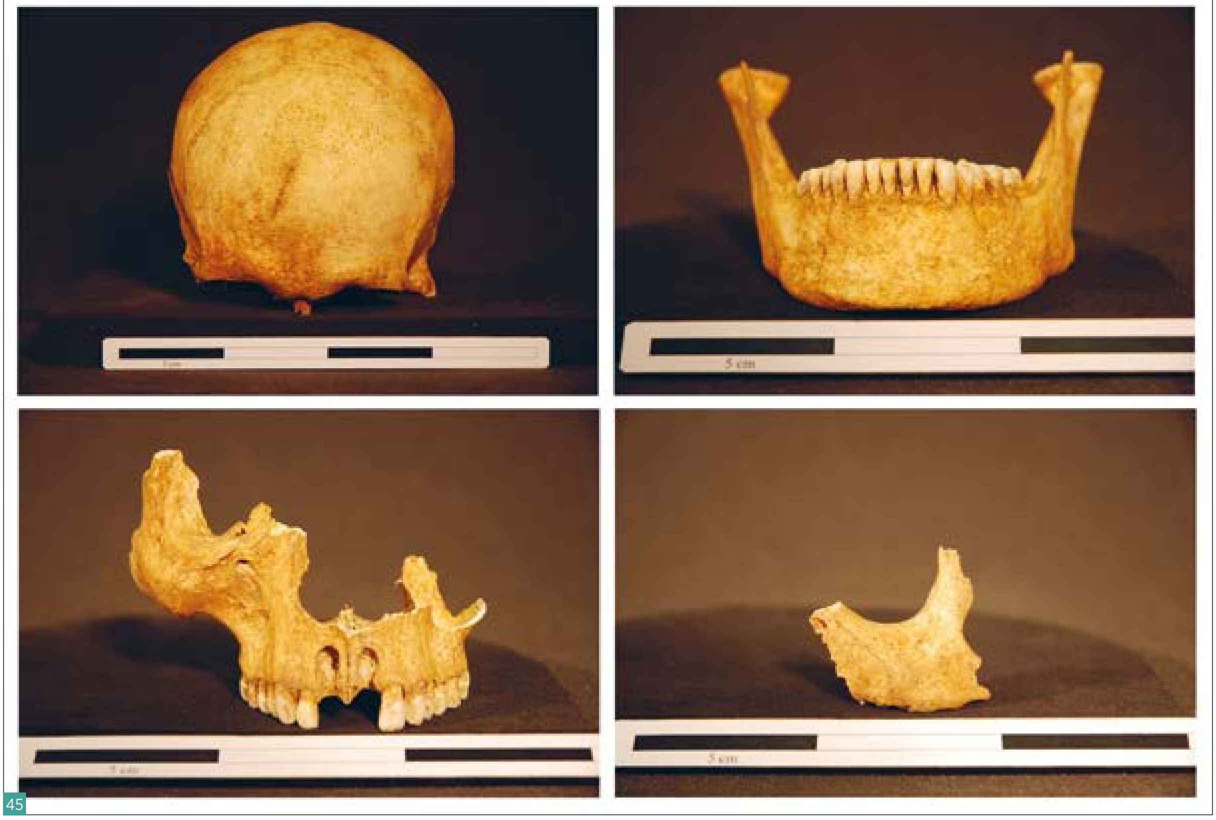
One response to this was the development of the London Charter in 2006, a document with international scope which outlines principles of best practice in heritage visualisation. It reinforces the role that digital methods play in fostering dialogue and academic discourse in research, but also in presenting information to wider audiences. Case studies in this section look at examples of where fragmented evidence has been virtually brought together under expert guidance to visualise speculative historical designs and reconstructions.

3.1.5. Stirling Castle cranial remains

Archaeological excavations at Stirling Castle between 1997 and 2004 revealed human remains of eleven individuals. The remains were carbon dated to the mid-13th to 16th centuries, over a span of 300 years. As the excavations were undertaken as part of ongoing works at the castle, the remains were planned to be reinterred prior to completion of the re-flooring works. To explore the potential of making human remains available for further study after reinterrment, a selection of skull fragments for one individual were laser scanned by HES to create an accurate 3D record.

The project aimed to assemble the four main constituent skull fragments (shown in Fig. 45) using digital methods, which provided a non-contact method for recording and visualising the skull. The fragments were captured in 3D using a triangulated laser scanner, providing sub-millimetre resolution and accuracy. Specific challenges to the scanning included: highly complex nasal filaments, the self-occluding nature of the skull's shape and thinness of certain elements such as the zygomatic bone. The scattering, glossy-reflective material of the teeth also posed a problem for the laser, which captured the data with significantly higher levels of noise than the other bone surfaces. The fragility of the remains precluded the use of casting to acquire better data, and applying a matting material to the sample to improve laser reflection would potentially contaminate the teeth in any future analysis.

Fig. 45 Photographs showing the separate fragments of skull belonging to the individual.



45

Assembly of the parts allowed the skull to be visualised in 3D to resemble its in-tact form, as shown in Fig. 46. The absence of texture information from the skull and use of material shaders also firmly highlighted the damage to the skull, including a significant cranial wound and other signs of injury.

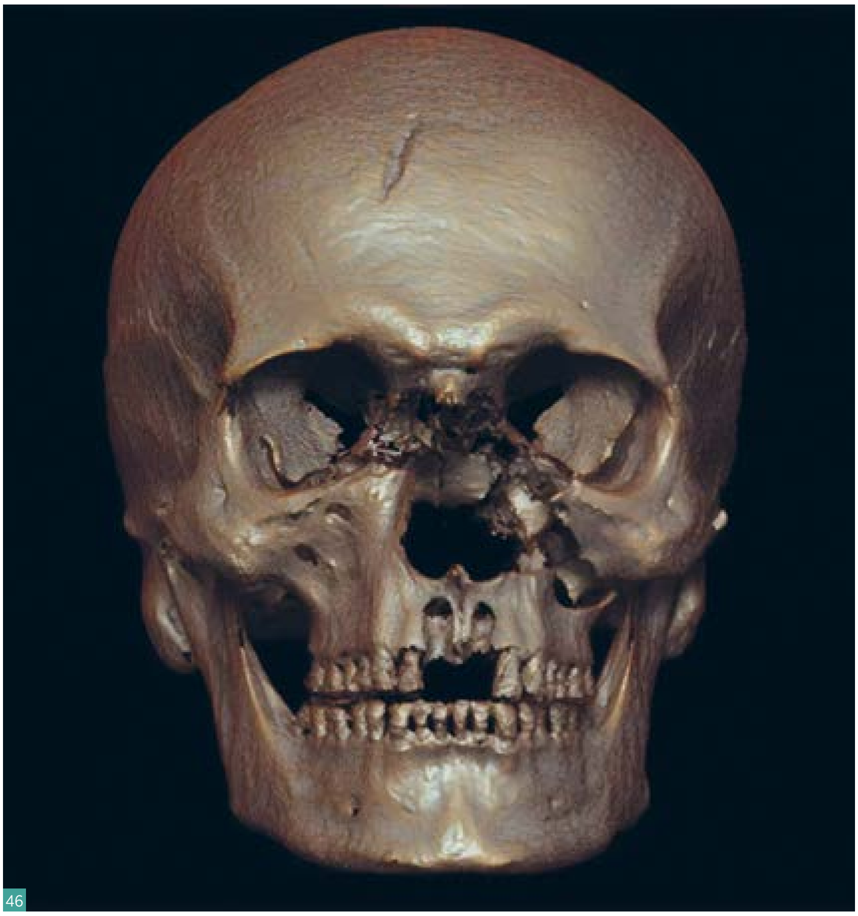


Fig. 46 The assembled model containing the scanned skull fragments.

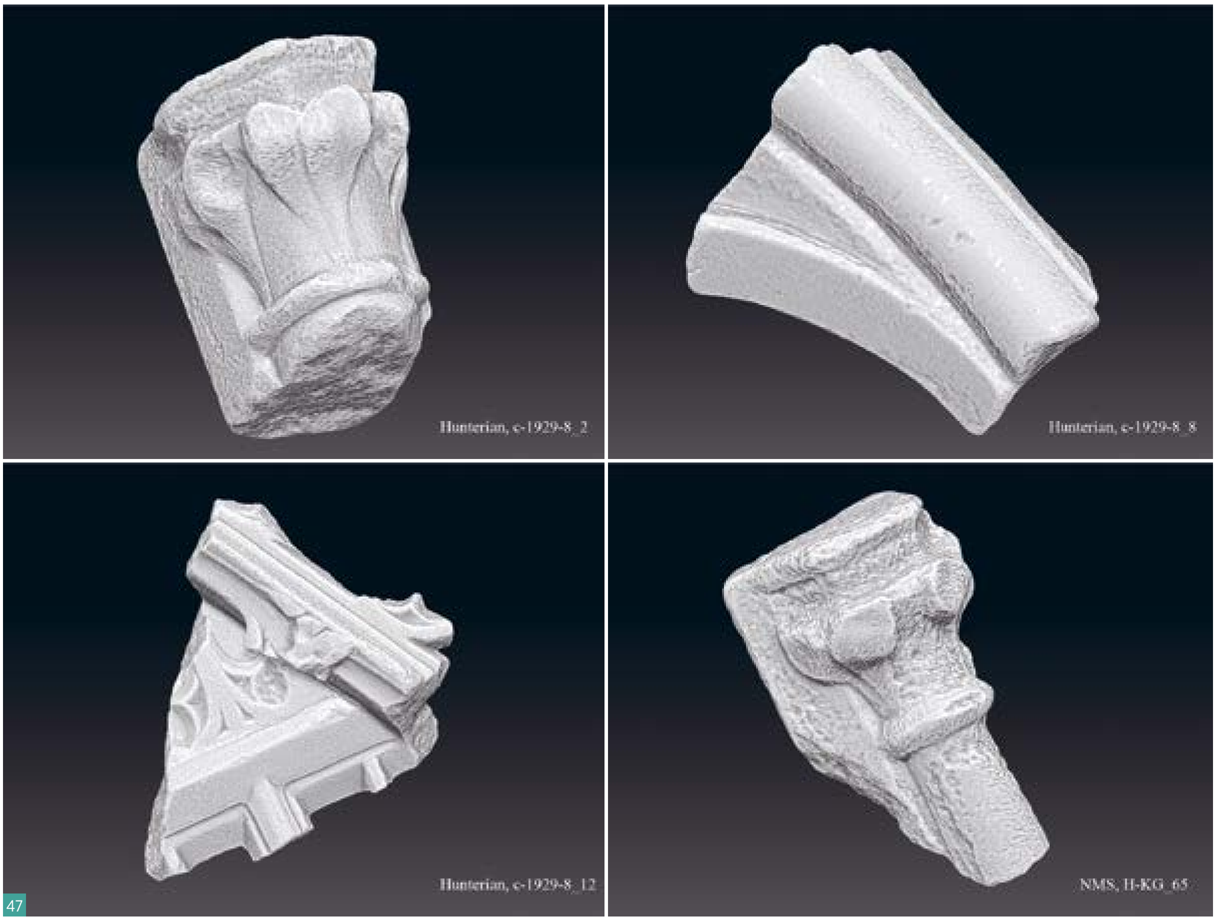
The exploratory project led to the development of a full facial reconstruction of the skull by researchers at the University of Dundee using digital methods and painting by a medical artist. From this research and prior observations, the individual was identified as a knight aged 26-35 that had sustained 44 skull fractures from a blunt object. Reconstructions of a male and a female, also amongst the remains, were exhibited at the castle at the opening of the palace in 2011.

3.1.6. Robert the Bruce tomb

In 2014 the CDDV worked as part of a collaborative project to develop a speculative 3D reconstruction of the tomb of Robert the Bruce. The project was intended to create novel visualisations for public exhibition at museums and galleries. Its launch garnered a high profile and generated wide public engagement. To deliver the project, the CDDV worked in coordination with partners at HES, the Hunterian Museum, the University of Glasgow, the University of St Andrews and the National Museum of Scotland.

The reconstruction was centred around fragments of the tomb, the only remaining material evidence, which were used to form a virtual reassembly based on contemporary workmanship, design and historical evidence. Visualising the tomb brought forward competing ideas on the monument's design, with the presentation of supporting evidence and academic study used to justify and evaluate the model. The fragments were laser scanned by HES using close-range techniques and used to provide a scaled reference for the foundation of the reconstruction. HES also provided the principal interpretation for the reconstructed tomb, whose study of the fragments (some of which are pictured in Fig. 47) enabled the CDDV's artists to design and colour the model.

Fig. 47 Laser scan data of several fragments from the tomb of Robert the Bruce.



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Components of the design included the creation of an effigy and decorative elements shown in Fig. 48. The modelling process was undertaken to enable its use as a basis for fabrication, accurately scaled and constructed from manifold geometry, features that are not typically requirements of projects solely for visualisation. The modelling workflow also generated discussion on the specifics of the tomb's design, including materials (Fig. 49). To convey this, specific material shaders were developed for the rendered visualisations including glossy polished black stone, subsurface scatting of the marble and gold leaf.

48

Fig. 48 Plan view of the rendered 3D model of Robert the Bruce's tomb.

49

Fig. 49 Side elevation view of the rendered 3D model of Robert the Bruce's tomb.

A range of rendered images and animations of the 3D model were produced for the project and used as a core component of the interpretive content made available at the exhibitions. In addition, a physical Computer Numerical Controlled (CNC) milled scale-model of the tomb was produced in polyurethane foam for use in museum exhibitions.

3.1.7. Conservation monitoring

Change observed at cultural heritage sites may be associated with challenges to the conservation of the site or its environmental context, and may reflect deterioration of its condition or developing threats that require remedial action. Digital documentation provides methodologies and tools that are suited for mapping physical change and, when integrated with other techniques available to conservation science, can build up a picture of how issues such as moisture ingress of buildings or weathering and erosion are impacting the integrity of the sites. Undertaking periodic survey and data capture can highlight the magnitude and rate of change, helping to inform specialists and guide decisions about schemes of conservation. In order to create a record of its properties in care using digital documentation, HES has committed to the 'Rae' project to digitally record all of its sites, monuments and objects in collections. The project also aims to facilitate a range of uses to aid in the conservation, management and promotion of the sites. The survey 3D datasets incorporate control networks, including permanent survey markers to provide a static baseline for subsequent surveys.

3.1.8. Multiple techniques and combined datasets

A laser scanning survey of Skelmorlie Aisle in Ayrshire was undertaken by HES as part of its Rae project. The site's basement level crypt was noticed to suffer from moisture ingress which had led to stone degradation of the building's masonry. A moisture analysis survey undertaken in 2013 showed the extent of the problem. The dataset from the moisture survey was later projected onto the 3D dataset to better show the relationship of the moisture ingress to the structure of the tomb. Fig. 50 shows the initial results of this process, with the rest of the church displayed in greyscale laser return intensity.

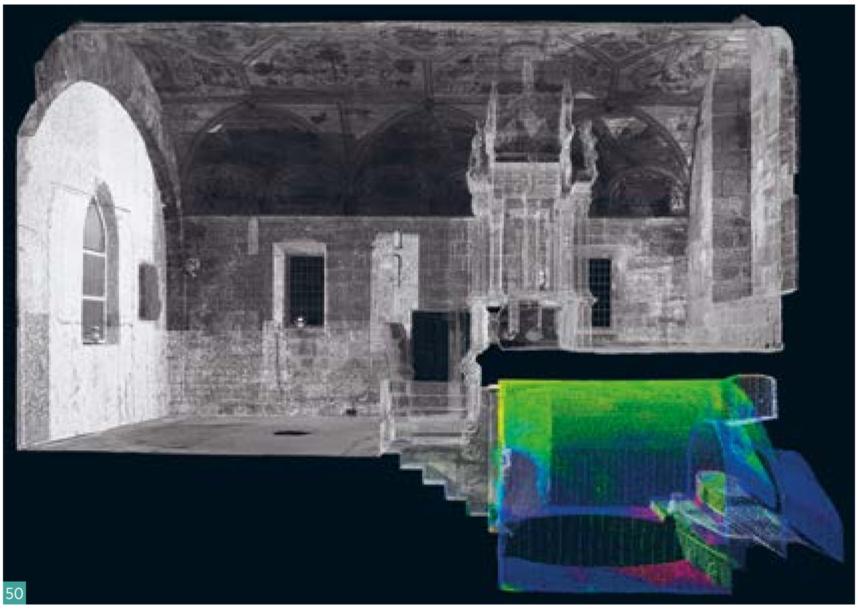
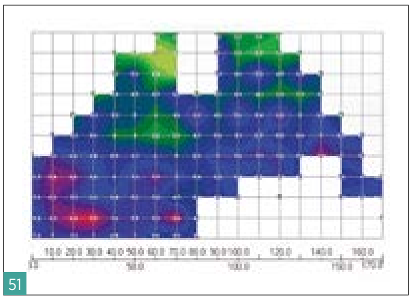


Fig. 50 Cross-section elevation view of Skelmorlie Aisle with crypt showing mapped moisture data.

The spatial dataset was captured using terrestrial laser scanning to record the interior and exterior of the church. The moisture survey was undertaken with a microwave moisture meter able to penetrate up to 20-30cm into the stone substrate non-destructively. Its dataset is typically viewed in a 2D array pattern as shown in Fig. 51, which shows colour-graded values representing percentage moisture content. This was projected onto the 3D point cloud of the crypt in Leica Geosystem's Cyclone (Fig. 52), with common pick-points between the moisture map and the laser scanning dataset. This process was repeated for the crypt elevations and the floor.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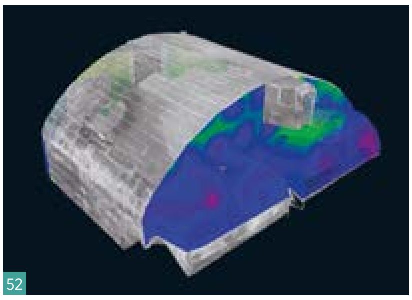
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Fig. 51 Moisture map shown in typical 2D array view. Colour gradient corresponds to intensity values of meter readings.

Fig. 52 Skelmorlie Aisle moisture data mapped to the interior of the crypt.

At Rosslyn chapel in Midlothian, a thermographic imaging survey was undertaken to identify heat loss between the older structure and the later Victorian vestry. Fig. 53 shows the combined view of the meshed 3D terrestrial laser scan data and overlaid thermography. The colour gradient indicates temperature, with blue and cyan denoting the lower temperature areas, green the median, and yellow and red indicating areas of higher temperature. A clear 'hot-spot' is visible between the vestry masonry and the fabric of the original structure.

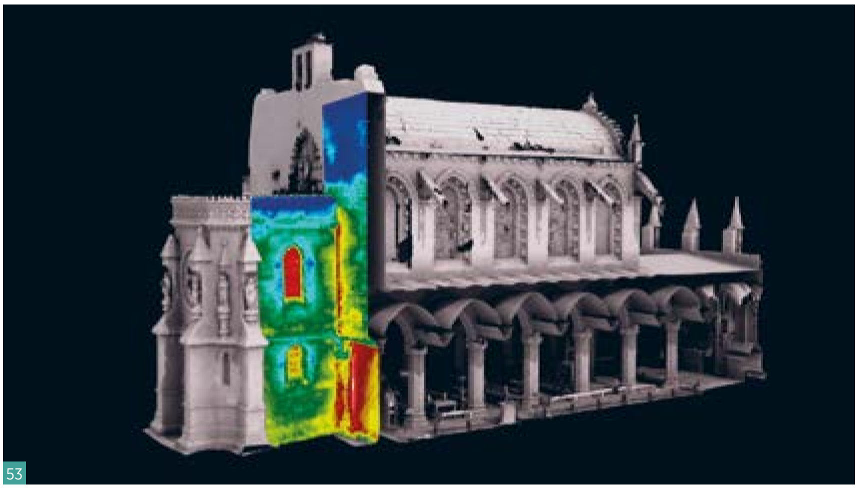
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Fig. 53 Thermography overlaid on top of the 3D mesh of Rosslyn Chapel.

Presenting the data in a more visual way is useful for the conservation professional as it can highlight relationships between recorded values and the structure of the site itself, helping to identify problem areas more easily. It can also be used to better communicate these issues to other audiences including non-specialists and members of the public. The moisture survey at Skelmorlie Aisle was used to inform a plan of action to address the issues. This resulted in the installation of conservation heaters to reduce moisture penetration and further deterioration of the stone.

3.1.9. Monitoring at Rosslyn Chapel

Following the complete digital documentation of Rosslyn Chapel in 2010, a scheme of monitoring commenced in 2012 to undertake 5-yearly re-scanning of selected areas. The data capture consisted of the use of close-range scanning techniques including triangulated laser scanning and structured light scanning (SLS). The data is being used to identify and quantify any erosion caused by weathering. Fig. 54 shows scanning in progress using the Konica VIVID 9i triangulated laser scanner and Artec MHT structured light scanner.


54a

Fig. 54a Laser scanning a Rosslyn Chapel turret with the Konica Minolta VIVID 9i for condition monitoring.


54b

Fig. 54b Structured light scanning at Rosslyn Chapel with an Artec MHT for condition monitoring.

Structured light scanning was selected to capture the overall geometry of the selected elements (in this case the ornate carved turrets). The scanner specifications are sub-millimetre but list lower accuracy and resolution tolerances than the triangulated scanner, whilst the dataset is assembled using registration of multiple sub-frames. The data captured with the triangulated scanner would be used to compare single swathes directly, enabling more accurate and higher resolution comparisons for key areas whilst avoiding the introduction of error and noise from processing and registration. Fig. 55 shows the location of these sub-scans that identified key areas directed to the documentation team by conservation personnel.

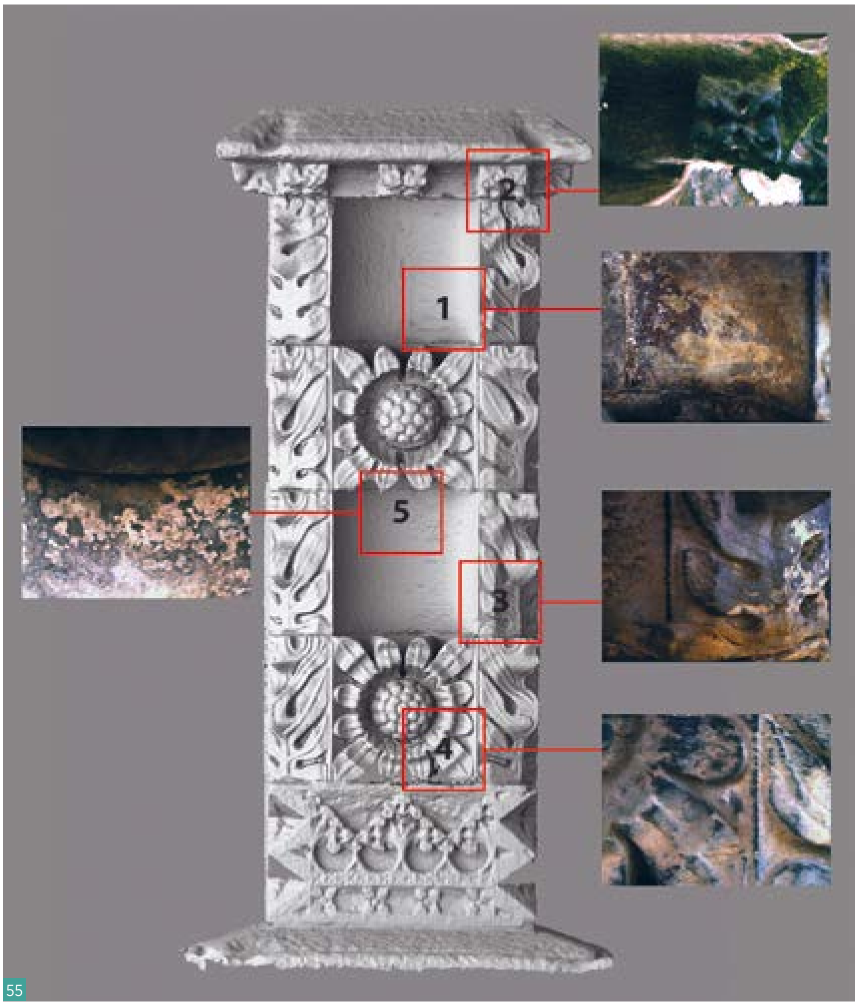


Fig. 55 Orthographic render of the Rosslyn chapel turret data, annotated to show the location of swathes of higher resolution data.

The results from the monitoring at Rosslyn will help to determine any impact from weathering and erosion of the historic fabric for these areas. Re-scanning will be undertaken in 2017 to provide a comparative dataset.

3.1.10. Environmental monitoring and climate change at Skara Brae

A set of different challenges are posed by coastal erosion and changing environmental conditions at Skara Brae Neolithic settlement in Orkney. Increasing storminess and sea level rise present a significant threat to the site, which sits adjacent to the shoreline at the Bay of Skaill. It is part of the Heart of Neolithic Orkney World Heritage Site and a wider archaeological landscape. Sea defences were erected for the site in the late 1920's and repeatedly strengthened over the years. Concern for the coastline and dunes immediately to the east and west of the site led to the start of a programme of biennial surveys in 2014 to monitor erosion of the surrounding beach and bank. A subsequent survey in 2016 provided a comparative dataset to identify changes. This scheme of monitoring was developed by HES as part of its wider Rae project to digitally document its properties in care.

The survey methodology is designed to be repeatable, based on a traverse with references to permanent survey markers established on site. Terrestrial laser scanning is used to capture the primary spatial dataset and ties into the control network (Fig. 56). GNSS is used to geolocate the datasets.

Fig. 56 Survey traverse at Skara Brae beach.

To provide comparative analysis, the datasets from both 2014 and 2016 epochs were topologised as meshes using point cloud and 3D mesh creation software 3DReshaper. Topological deviation between data from both surveys was identified and presented with a colour gradient to indicate areas of change (Fig. 57). Initial results appear to show a complex situation with some areas of build-up and some of reduction, with the most noticeable loss (100-200mm difference) to the bank to the west of the site.

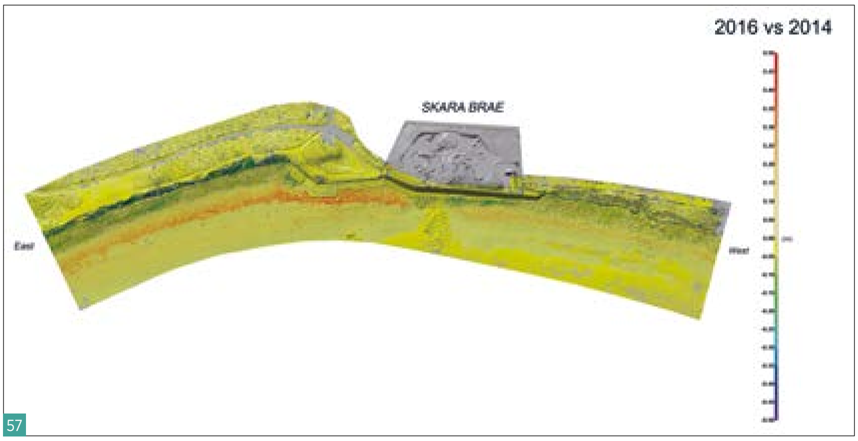


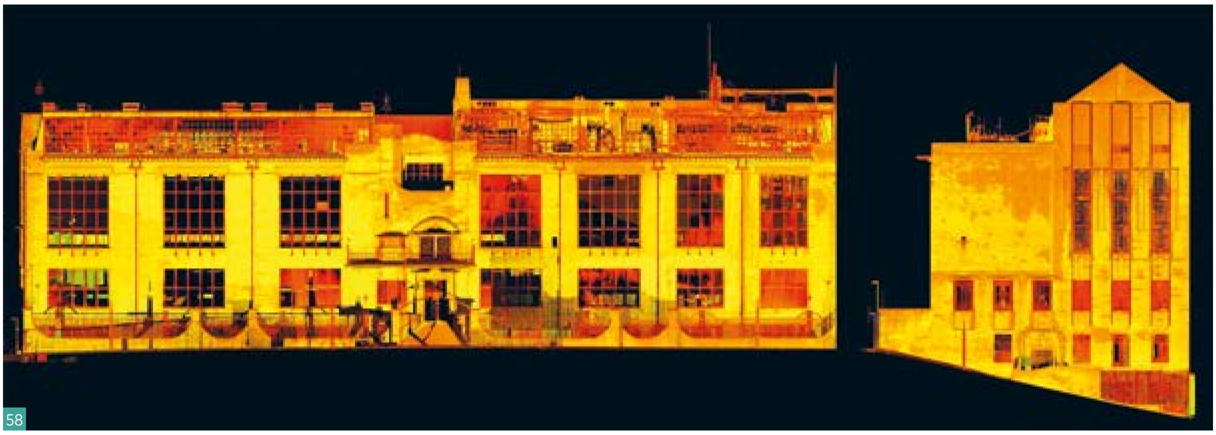
Fig. 57 Comparative analysis of data captured at Skara Brae in 2016 vs 2014. Gradient key shows that red colour corresponds to accretion or expansion, yellow indicates minimal change and green indicates loss.

Subsequent surveys will provide a clearer picture to identify trends in the long term, help to quantify differences and provide data for decision making. Through provision of data, HES are working with Scottish Natural Heritage, to help improve the resolution of existing 2D datasets monitoring the tidal sea level for Orkney.

3.1.11. Structural deviation at the Glasgow School of Art Mackintosh building

The Glasgow School of Art's Mackintosh building suffered substantial fire damage in May 2014, particularly to the western wing, including interiors, roof and facade. Efforts to assess the extent of the damage included an immediate scheme of post-fire terrestrial laser scanning (Fig. 58). This included coverage of the exterior and affected interior spaces.

Fig. 58 Laser scan data from the post-fire Glasgow School of Art Mackintosh building exterior.



Fire and subsequent water damage affected the interior spaces, and charring of the gable support timbers raised concerns from building control officials of the western façade's structural integrity. To aid decision making and provide analytical information, previous data from exterior scanning undertaken in 2008 was used as a baseline to produce a deviation map of the western façade and the western gable end (Fig. 59).

Fig. 59 Deviation map from the Glasgow School of Art's Mackintosh building with point measurements taken from specific stones. Differences calculated between two scans, pre-fire (2008) and post-fire (2014). Green and yellow signify movement of <20mm on the x-axis, purple and orange signify movement of >20mm on the x-axis.

In the days immediately following the fire, the documentation team worked with the Glasgow City Council Building Control inspectors and conservation architects from HES to evaluate the information from condition monitoring. Analysis showed that the most substantial movement was to the upper gable, which was agreed would be disassembled. Deviation to the remaining western façade was shown to be within a tolerable safe limit, which allowed the majority of fabric of the building to be kept intact.

3.2. Building Information Modelling (BIM)

Building Information Modelling (BIM) is a system that represents built assets within a digital platform to enhance decision making, planning and collaborative working for its lifecycle. Its introduction and use within the construction industry aims to improve processes and the availability and consistency of information for those involved at all stages. It is a system that can be used for new constructions from their inception but also existing structures through using 3D data capture techniques to translate built assets into digital form. The utility of a BIM depends on how much information can be associated with the assets, which directly informs its usefulness for various purposes such as energy and structural performance as well as economic analysis.

BIM can be applied to existing facilities and built heritage, where assets are represented by using data capture methodologies such as terrestrial laser scanning to record sites in their present condition for modelling purposes. This data can then be assembled with information from different sources and surveys, such as fire action plans, mechanical, electrical and plumbing, to develop an Asset Information Model (AIM). The AIM acts as a central resource for information and decision making about the building, and basic uses could include generating reports, e.g. showing that there are [x] number of fire extinguishers in a building, of which [y] are type [z]. The same system, with the appropriate information, could assess energy performance and help to plan refurbishments to improve building sustainability.

Level of Development and Level of Detail (LoD) govern what information will be included specifically in the BIM, and it is common for more than one to exist for the same site or building depending on purpose. Level of Detail refers to the amount of visual information displayed for an asset; Level of Development describes the extent of attribute information for specific assets (e.g. a basic description of required asset, or a full manufacturer's specification).

Adoption of BIM in the UK has also been driven by the government, which in 2011 published the Government Construction Strategy requiring collaborative 3D BIM for all its construction projects by 2016. Further information on BIM can be found at Royal Institute of Chartered Surveyors (RICS, online at *www.rics.org*), the UK government BIM Task Group (*www.bimtaskgroup.org*) and the British Standards Institution (*www.bsigroup.com*). The Scottish Futures Trust supports government objectives with its BIM Delivery Group, bringing together expertise from academia, industry and the public sector (*www.scottishfuturestrust.org.uk*). Special interest group BIM4Heritage aims to raise awareness and promote understanding of BIM within conservation and the heritage sector (*www.bim4heritage.org*).

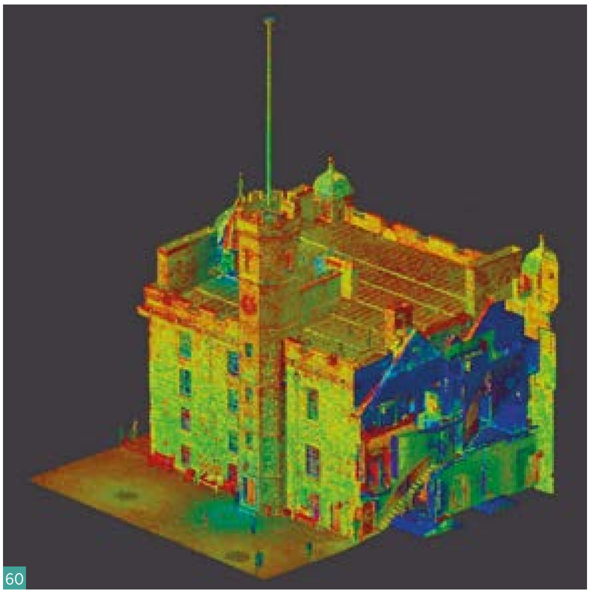
3.2.1. Edinburgh Castle Royal Palace

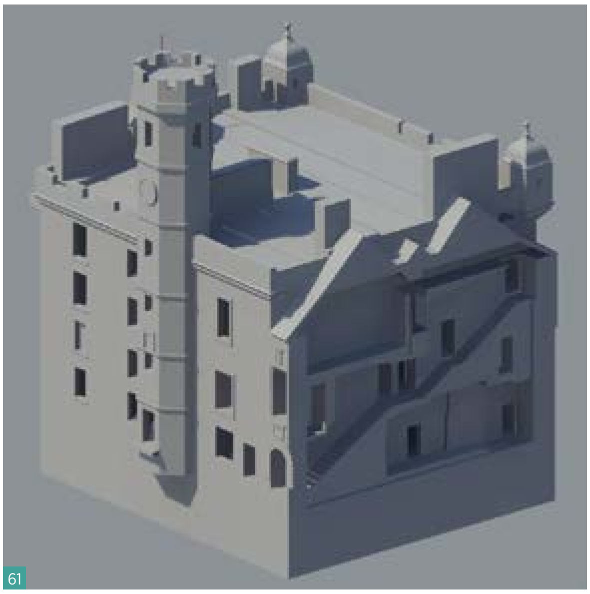
Historic Environment Scotland (HES) formed an initiative to apply BIM to a selection of sites and projects within its estate. This was in response to the strategic recommendation by the Scottish Government to implement BIM where appropriate by April 2017. It also represented an opportunity to improve access to reliable asset information, improve decision-making and build organisational skills and capacity. Edinburgh Castle's Royal Palace formed a key case study as part of this initiative, identifying the role of BIM in supporting operational and facilities management. It would also provide information for a potential capital project for the conservation and interpretation of the historic royal apartments. Due to the complexity of the castle as a site with multiple phases and irregular, unique construction, it presents an opportunity to develop better workflows for creating a BIM based on site survey data of historic structures and a wide range of assets.

The methodology for the creation of the 3D assets followed a 'scan-to-BIM' approach, using point clouds created by terrestrial laser scanning as the basis for 3D modelling the building. This survey of the building captured interiors and exteriors, recording the historic fabric of the building but also modern plant rooms and facilities. Areas of the building that were inaccessible during the survey were supplemented with spatial information from existing drawings produced by measured survey within a 10-20 year window for reliability. Fig. 60 shows the point cloud dataset used as the basis for the project, which was modelled to represent the fabric of the building shown in Fig. 61.

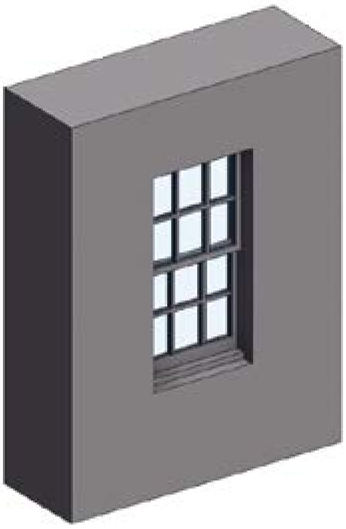
Fig. 60 Cutaway point cloud of the Royal Palace from terrestrial laser scanning, colours show laser intensity values.

Fig. 61 Cutaway 3D modelled geometry.

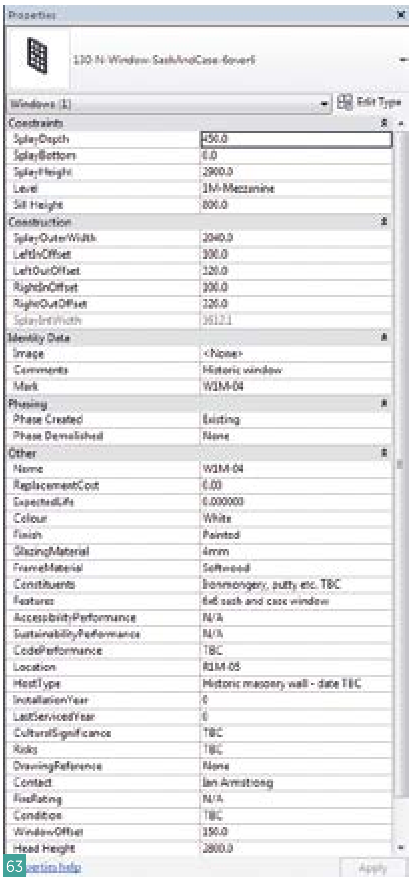

60


61

The model was populated with asset information, creating a library of components based on information entered. Standard types of objects were identified and placed throughout the building, such as doors and windows, including sub-types (fixed casement, sash, etc.) and their attributes. Fig. 62 illustrates the modelled asset for one type of window from the project, and its associated properties in can be seen in Fig. 63.



62



63

Constraints	
SplayDepth	450.0
SplayBottom	0.0
SplayHeight	2900.0
Level	1M-Mezzanine
Sill Height	800.0
Construction	
SplayOuterWidth	2040.0
LeftInOffset	300.0
LeftOutOffset	120.0
RightInOffset	300.0
RightOutOffset	120.0
SplayIntWidth	2612.1
Identity Data	
Image	<None>
Comments	Historic window
Mark	W1M-04
Phasing	
Phase Created	Existing
Phase Demolished	None
Other	
Name	W1M-04
ReplacementCost	0.00
ExpectedLife	0.000000
Colour	White
Finish	Painted
GlazingMaterial	4mm
FrameMaterial	Softwood
Constituents	Ironmongery, putty etc. TBC
Features	6x6 sash and case window
AccessibilityPerformance	N/A
SustainabilityPerformance	N/A
CodePerformance	TBC
Location	R1M-05
HostType	Historic masonry wall - date TBC
InstallationYear	0
LastServicedYear	0
CulturalSignificance	TBC
Risks	TBC
DrawingReference	None
Contact	Ian Armstrong
FireRating	N/A
Condition	TBC
WindowOffset	150.0
Head Height	2800.0

Fig. 62 Modelled representation of a sash window from the Royal Palace.

Fig. 63 Attributes assigned to the specific window.

The active integration of other assets includes structural components from records, fire safety systems, mechanical and electrical systems. This information is provided by specialists to ensure that it is integrated into the BIM resource correctly. This information can be accessed to show the different modelled representations of the building and filter pertinent information based on application.

3.3. Interpretation

Digital techniques allow for a wider set of resources for interpretation in cultural heritage. They enable novel ways of presenting information to specialist and non-specialist audiences for education, and offer new ways to engage the public with historic sites and collections. The following case studies identify projects that have used digital documentation techniques to enhance understanding of cultural heritage sites and objects to promote learning, community engagement and original research.

3.3.1. Replication via 3D printing and CNC milling

Fabrication of replicated historic objects and artefacts can provide useful tools for interpretation, enabling study and wide distribution. Techniques for replication have long existed and seen use in conservation and display, typically in the form of casting and the creation of moulds, which involve contact with the surface of the object. Digital documentation workflows enable a method for replication that is non-contact through 3D scanning, offering a more sustainable technique for reproduction and presenting an option for material that may be friable or otherwise too delicate for casting. The captured data is processed and prepared as a model that can be used for fabrication, which typically involves ensuring the model is 'watertight' by correcting non-manifold geometry (such as reversed adjacent surface normals, open edges or overlapping polygons). This fabrication process is often referred to as 'rapid prototyping' and covers an umbrella of techniques.

Additive manufacturing is more commonly referred to as 3D printing, and is the process of fabricating an object through building up layers of material into a complete form. Materials can vary, from polymers to ceramics and metals, and the resultant prints can also be used as the base for a mould to be cast. 3D printing methods calculate how the physical object will be fabricated by dividing it into discrete layers and pre-calculating the movement of either the print bed or the nozzle head/laser, depending on the technique. There are a number of 3D printing technologies; many of these operate differently and work to different accuracy and resolution tolerances for the printed object. These have been broadly categorised in standards documentation by ASTM International. For further reading, the ISO/ASTM 52900:2015 standard is available online (*www.iso.org*) and in print.

Subtractive manufacturing, by contrast, is the fabrication of objects through the selective removal of material from a main piece of material. This is typically through a process such as Computer Numerical Control (CNC) milling which operates by moving and rotating a cutting tool across multiple axes. The materials that can be milled are only limited to those that can be worked with by tools, and typical examples include metal, wood and stone. CNC milling uses pre-calculated tool paths based on the input geometry to determine the operation of the cutting tool. The resultant object may need to be finished or cleaned by hand to remove toolmarks or smooth unwanted contours.

3.3.2. The Bridgeness slab reproduction

In 2010, a project began to produce a replica of the Romano-British carved stone the ‘Bridgeness slab’, and instate it in a public setting. As the original stone is maintained on display at the National Museum of Scotland in Edinburgh, this would provide an accurate surrogate to allow public engagement and further convey interpretation of the historical artefact in its original location. The methodology of the project employed close-range scanning to acquire an accurate and high resolution 3D dataset, which would be used as the basis for CNC milling a stone reproduction of the original relief.

Data capture was undertaken with a Konica Minolta VIVID 9i triangulated laser scanner, allowing sub-millimetre accuracies to be achieved. The scanner was mounted on a high elevation tripod and moved longitudinally and in vertical columns to maximise coverage of the relief. The scanning (Fig. 64) was undertaken at the National Museum of Scotland in Edinburgh outside of public opening hours for unimpeded access.


64

Fig. 64 Capturing the Bridgeness slab with a Konica Minolta VIVID 9i triangulated laser scanner.

Registration and processing of the scans into a 3D modelled object produced a 'watertight' geometric object for the CNC milling process. Fig. 65 shows a rendered image of the assembled and processed dataset. Processing included 'hole-filling' for any areas in the absence of data and to ensure the geometry was manifold for further use.


65

Fig. 65 A rendered view of the Bridgeness slab 3D laser scan data.

The requirements to produce the CNC milled version were challenging and required substantial effort to source. Obtaining a single piece of appropriate sandstone large enough to produce the stone meant waiting for material specifically quarried for the purpose. In addition, the stone required a CNC machine with a bed size capable of taking such a substantial single stone. The milling process was undertaken over two weeks with a tool-head of 2-3mm diameter to reproduce the stone's topology. Removing the CNC tool marks and finishing the stone by hand (Fig. 66) took a further two weeks.


66

Fig. 66 The CNC milled Bridgeness slab stone being finished by hand. Image courtesy of Falkirk Council.

The reproduced slab was unveiled within its public setting at Bridgeness with the aim of becoming a community focal point, with a display and revealing of the stone arranged for the public and press in 2012 (Fig. 67). This was alongside the release and subsequent showing of a documentary film in a local cinema describing the historical significance of the stone and the project surrounding its reproduction.

Fig. 67a Public unveiling of the replica slab located in Bridgeness.

Fig. 67b Detail of the finished Bridgeness Slab replica.

3.3.3. Elgin Cathedral

3D printing was employed at Elgin Cathedral by HES to replicate decorative carved stone elements of the building that are poorly visible and physically out of reach. The project was commissioned to aid interpretation and enhance visitor experience, with the fabricated objects situated in a specially constructed interpretation suite. This would have the added benefit of making the overall site more accessible to visitors, whilst also presenting new options for blind or visually impaired visitors.

The objective of the 3D data capture and fabrication was to create two handling kits, each with 12 carved stones at 30% scale. Structured light scanning and photogrammetry were used to capture high resolution 3D datasets that were subsequently processed to into watertight geometry for 3D printing. Fig. 68 shows a rendered visualisation of the processed geometry from one stone (a 'vault boss', used to adorn ribs on the vaulted ceiling) shown with a basic material shader. The 3D printing was undertaken in-house using a PolyJet technique (which builds up layers of photopolymer and cures with UV light during the printing process), with the capability to print at a thickness between 0.028mm and 0.016mm per layer. Fig. 69 shows the cleaned 3D prints produced for one of the Elgin Cathedral vault bosses (ELG/VB/16).


68


69

Fig. 68 Elgin vault boss (ELG/VB/16) 3D scan data.

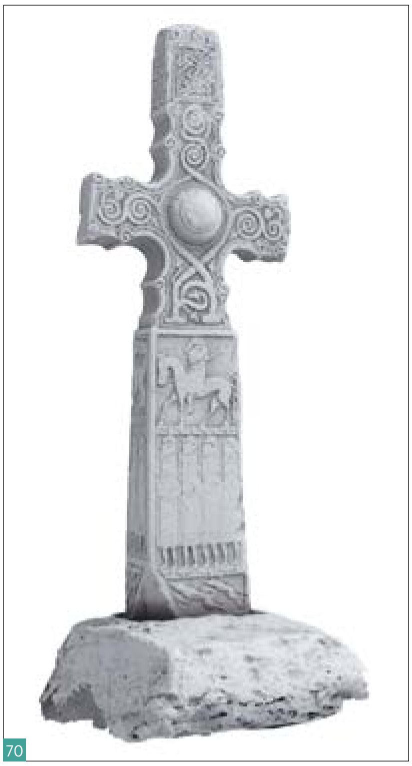
Fig. 69 Elgin vault boss 3D polymer prints.

In addition to being an accurate resource to engage site visitors, the replica heads are being incorporated into activity plans for school groups.

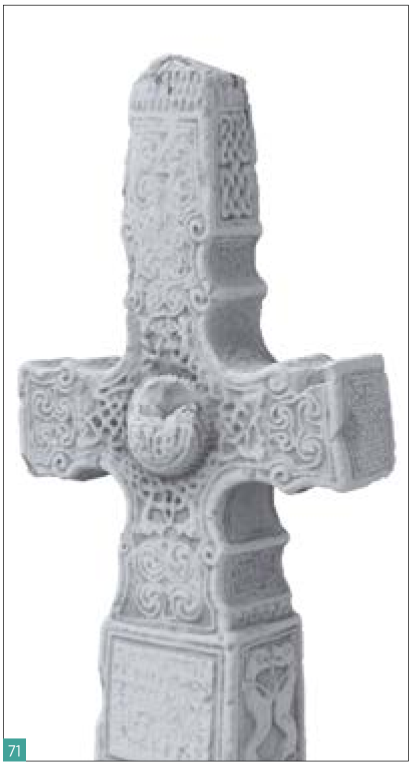
3.3.4. Worn inscription analysis of the Dupplin Cross panel

The Dupplin cross is a 9th century AD carved Pictish cross, standing 3m in height and located at St Serf's Church in Dunning, Scotland. It is inscribed with various scenes including traditional Pictish decorative, figurative and animal carvings. It also contains an epigraphic panel with a shallow and weathered Pictish inscription that reads 'Cus[an]tin filius Fircus[su]...', referring to the contemporary Pictish king Constantine, son of Fergus. The Cross was laser scanned in 2008 for a CDDV project recording the monument at sub-millimetre resolution with a handheld Leica Geosystems T-scanner (dataset pictured in Fig. 70). The dataset was later used as part of an exploratory study looking at the application of scanning to the analysis of epigraphy. This was undertaken by an expert in Ogham inscriptions working with the CDDV.

The inscription was subject to a range of different visualisation techniques designed to enhance the heavily weathered and largely illegible text. A large part of the difficulty in interpreting the inscription derives from the rarity of similar epigraphy, poor documentation of the language and the poor condition of surviving examples. A range of material shaders were used to highlight the topology of the inscription, including increasing the specularity of the reflection parameters, and layering 'ambient occlusion' (Fig. 70 and Fig. 71) designed to shade geometry based on its surface occlusion from an ambient light source.



70



71

Fig. 70 Rendered view of the Dupplin Cross 3D laser scan data.

Fig. 71 Close-up view of the Dupplin Cross 3D data, showing the inscription panel at the foot of the Cross.

One approach amplified the Z axis of the surface, enhancing the peaks and valleys of the surface topology to exaggerate existing forms (see Fig. 72 and Fig. 73 for comparison). This method of visual enhancement emphasised the carved letters but also exaggerated the weathered stone surface detail, which did not contribute to legibility. As a result of the enhanced visualisation of the panel, small circular indentations were observed at the termini of letter strokes that may have been formed by drilling. This may indicate the remains of a carving technique seen in other instances, wherein the ends of strokes were first drilled then the letter was defined with a chisel or through 'pock-and-smooth' technique.

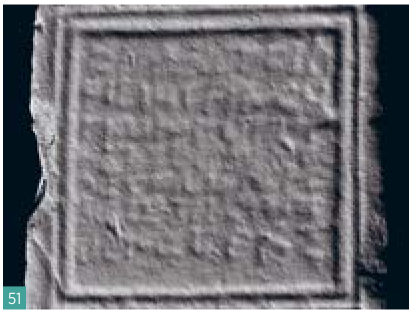


Fig. 72 Dupplin Cross panel 3D data with a standard material shader lit by an oblique light source.

Fig. 73 Dupplin Cross panel 3D data with an ambient occlusion shader enhanced in Adobe Photoshop.

The project concluded that the use of these techniques offers a powerful method of analysing epigraphy due to the options it presents for visualisation. The measured dataset also enables the use of statistical methods and comparative analysis to the corpus of other inscriptions of similar context and language. Ultimately, the analysis is limited by how weathered and illegible the stone has been rendered over time, but also the level of existing evidence and literature on the topic. The potential for discovery however is not just restricted to the textual content of the epigraphy as shown with the Dupplin Cross panel, but also the identification of tool marks and techniques associated with its carving.

3.3.5. Gamification

Digital documentation enables the creation of digital assets that can be incorporated into interactive real-time 3D gaming environments. This extends the possibility of developing virtual environments populated with representations of real world and reconstructed material, building environments that tap into the design and mechanics of interactive gaming. Developing narratives which have clear objectives and rewards for the viewer through rich natural and built 3D environments and animated characters, these can convey interpretations of cultural heritage sites in a way that traditional media cannot. Games in this format are referred to as 'serious games' and can be used to enhance visitor experience and to deliver educational content in an engaging way at different levels of learning.

3.3.6. 'Go Roman' Antonine Wall Bar Hill fort game

Spatial data for the Antonine Wall World Heritage Site that was captured as part of the Scottish Ten project was also used to develop the 'Go Roman' educational serious game on a mobile platform. The game was created by CDDV in collaboration with project partners the Bavarian State Department for Monument Protection (BLfD) and Austrian firm Edufilm und medien GmbH. Its aim was to engage younger audiences in the history of the site by presenting an interactive interpretation of Bar Hill Roman fort, a publicly accessible site situated on the Antonine Wall with very few extant remains. One playthrough narrative presents an interpretation of life at the fort from the perspective of slave girl 'Verecunda' around the age of eight. Players are presented with a series of tasks to accomplish in their role as a slave, which typically involve navigating around the fort and the adjacent civilian settlement ('vicus') to interact with objects or other characters.

Game assets were created with advice provided by archaeologists to improve the accuracy of the fort environment. A selection of specific models were based on data capture of real-world artefacts currently held in museum collections. These objects were pertinent to the environments and tasks assigned to the player, such as operating a quernstone, and other kitchen wares such as a Samian Ware vessel and a cheese press. Tasks were designed prior to the game development through storyboarding to drive the narrative and introduce the players to the fort. The characters were based on references to real people at the fort found on altars and graves. To make the characters more engaging they were animated with movement data derived from motion capture undertaken using actors, shown in Fig. 74.


74

Fig. 74 The motion capture setup used to record and map the animated movement of characters in the game world.

The design of the fort, its topography and layout based on a combination of terrestrial and aerial laser scanning undertaken for the Scottish Ten project. As the site has few extant remains, the reconstruction relied heavily on archaeological interpretation to inform the model. Fig. 75 shows the fort exterior model and the game interface allowing players to move around the world and check task progress.

Fig. 75 Screenshot from the Bar Hill game showing the exterior environment.

Character design and modelling was based on the lives of the inhabitants of the fort mainly identified in the game by their roles. The models were mapped with textures based on scans of real individuals to produce a more engaging interaction, shown in Fig. 76. Dialogue for the characters was developed for specific individuals relevant to the narrative, such as the fort cook who issues the player with orders and the produce sellers located in the vicus outside the fort. Fig. 77 shows an example of a dialogue interaction to begin a new task.

Fig. 76 Preview of some of the modelled Bar Hill game assets.

Fig. 77 Screenshot of in-game dialogue.

IntroQuest - Complete

They told me to start working here.

Yes? What do you want?

During development, testing included a session that involved play-through of the game with a class of primary school children, producing notes on the players' experience (Fig. 78). The feedback was positive and indicated that the game was engaging and educational. It also provided insight into how the game was used and highlighted bugs for fixing prior to release. The game 'Go Roman' is available for download on Android at the Google Play store and for iOS on Apple iTunes.

Fig. 78 Class of pupils testing the mobile platform game.

3.3.7. Visualisation

Projects undertaken for the purpose of visualisation often aim to communicate ideas, designs or conjectural scenarios in cultural heritage. The tools available to the 3D artist work well with the types of data produced by spatial and photographic capture methods, and include bespoke software suites for sculpting, modelling and animating. Moving beyond the representation of captured data may require skillsets more in common with fine art, and the use of multi-disciplinary teams has defined the capability of a number of CDDV projects. Common outputs may include pre-rendered still images and animations, which have traditionally employed workflows that used the best tools for example to calculate lighting, develop material shaders and render imagery. With the ongoing development of game engines, GPU hardware and increasingly accessible Virtual Reality, there are shifting workflows that change productivity and artistic options for developers.

3.3.8. Virtual repainting of Stirling Castle's James V

Figurative carvings decorating the Stirling Castle palace interior courtyard façade were virtually repainted to illustrate a speculative paint scheme. The project was undertaken in 2011 by the CDDV in coordination with HES and intended to create a set of rendered images and animations showing the hypothesised colour scheme applied to the castle. The multimedia outputs were used as a component of interpretive content for visitor display at the castle. The data from prior laser scanning and 3D modelling work at the castle provided a foundation to be used to situate the carvings within the wider visual context of the palace.

Whilst the previous laser scanning consisted of terrestrial methods, higher resolution data for the carvings was required to provide an accurate base for the 3D model. This was captured with a Leica T-Scanner, a triangulated laser scanner with sub-millimetre tolerances. One of the key Figs of James V is shown in Fig. 79 in unpainted and painted representations. The colour scheme was developed in coordination with expert historical advice from HES.

79

Fig. 79 Unpainted and painted versions of James V model.

The 3D models developed for the speculative paint scheme were incorporated into a transition animation, clearly indicating before and after representations of the carving. A further animation showed the carvings as part of the palace façade, also presented to show its identifiable 'harling' similar to the Stirling Castle Great Hall. Fig. 80 is a rendered still from this animation.

80

Fig. 80 Stirling Castle palace showing the lime harled façade with the painted Figs in context.

The project was successfully used at the castle as a means for conveying speculated historical phases and representations of built heritage. It allows the material to be illustrated to members of the public and for scholarly discourse alike, without the need to physically intervene on site, which may lead to a commitment to restoration or impede ongoing conservation of the physical heritage. Other case studies that have included visualisation of alternative paint schemes were also discussed earlier in section 3.1.

3.4. Accessibility

A defining feature of digital documentation is the ability of its methods to represent objects and sites in their three-dimensional nature, presented accurately and convincingly in their original context. For cultural heritage, this is key for communicating site experience and access to members of the public where sites or objects are inaccessible or remote. Furthermore, the rich, high resolution datasets enable study to academics where it may be unfeasible or impossible to have physical access to the subject matter. Key challenges for virtual access are shared with dissemination of the data, as using the digital assets may demand a learning curve, high-end computing hardware or specialist or technical guidance.

3.4.1. Dunadd Ogham inscription

The carved rock face at Dunadd in Argyll was laser-scanned at sub-millimetre resolution during a scheme of conservation in 2009 by HES. The stone also features a heavily weathered but complete early-medieval Ogham inscription. The digital project intended to assess the effectiveness of using digital capture and visualisation techniques for interpretation and scholarly study. Due to the inaccessibility of the stone under typical circumstances, the programme of data capture was used to create a high-resolution 3D dataset. An expert in Ogham inscription worked with the CDDV to develop an assessment of the epigraphy from the stone, in addition to analysis of the earlier-scanned Dupplin cross panel which also features an inscription. Fig. 81 shows an excerpt of the Dunadd 3D dataset.


81

Fig. 81 Rendered image showing a section of the Dunadd dataset. Ogham inscription visible in the centre.

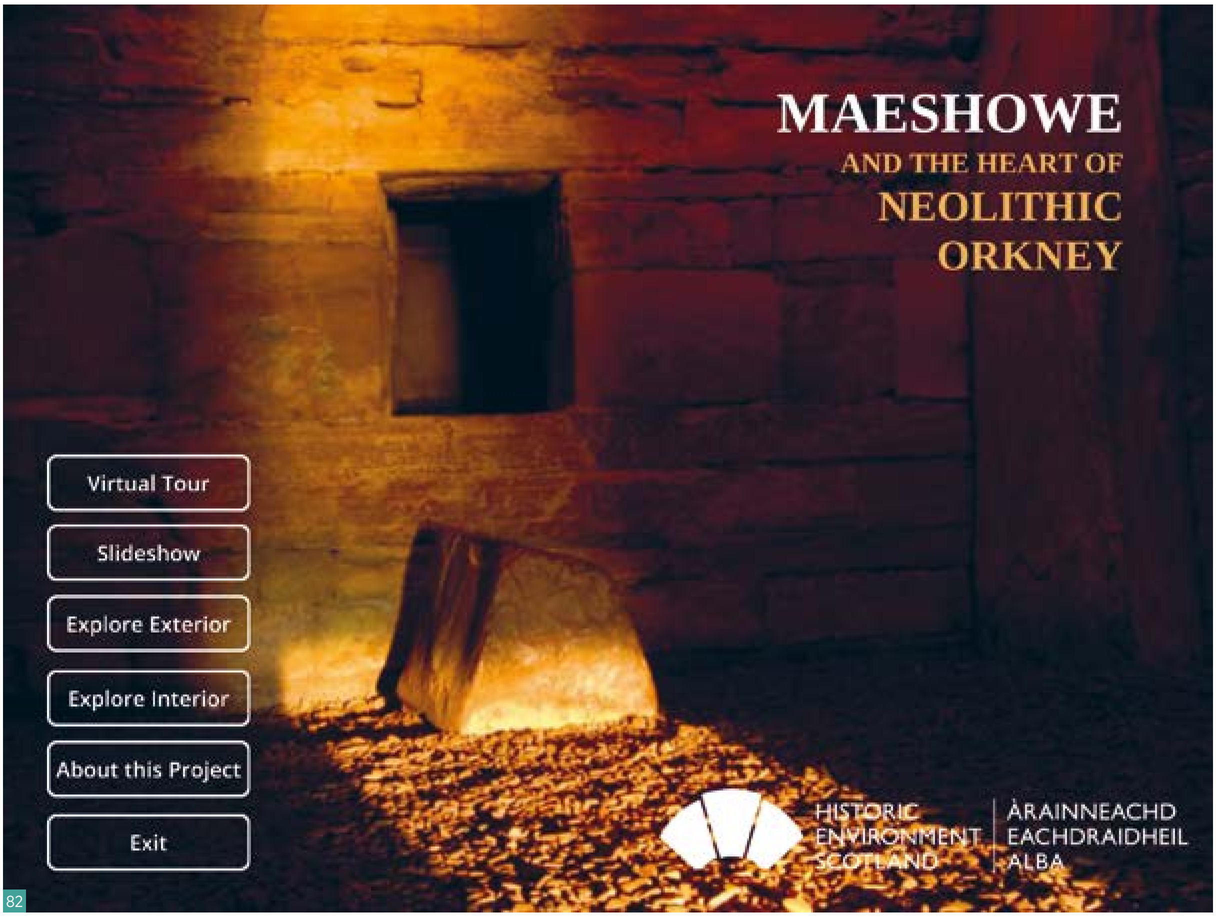
Parts of the Ogham inscription are clear, whilst others are damaged and have poor legibility. The ability to arbitrarily manipulate the viewing angle of the stone was particularly useful as the inscriptions were made on the side of seams in the stone, which itself lies embedded in-situ at Dunadd. Cross-sectioning the data allowed further investigation of the strokes of the script, which could offer insights into carving techniques and authorship of the epigraphy when compared with other examples. Visualising the stone without photo-textures applied further ‘de-contextualised’ the markings, allowing the surface topology to be analysed without interference from the colour properties of the stone.

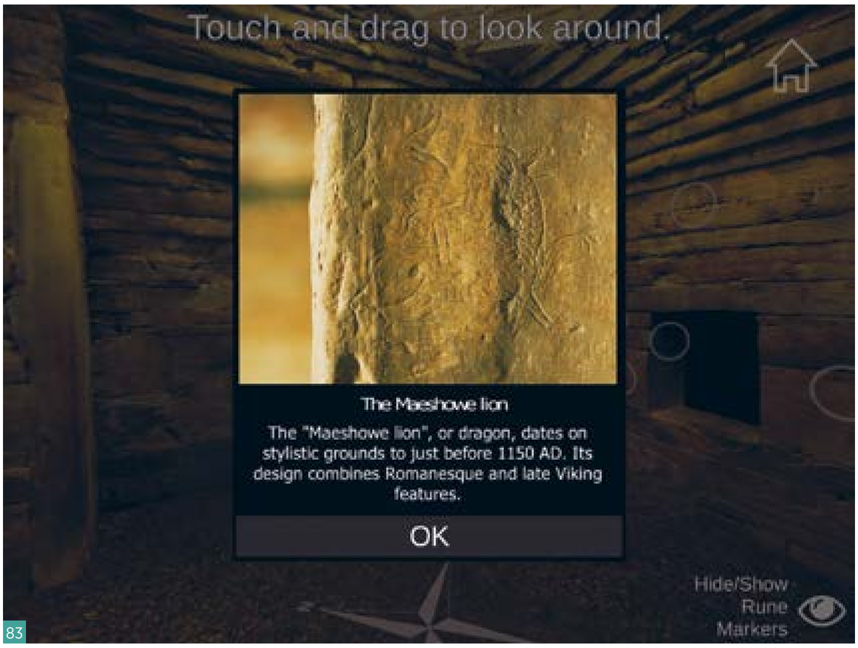
3.4.2. Remote access for Maeshowe Neolithic tomb

Following the digital documentation of Maeshowe Neolithic chambered tomb in Orkney as part of the Scottish Ten project, CDDV began developing an app with HES to enable virtual access. This was in response to a number of challenges to visitor access to the site including the difficult physical task of entering the interior chamber via a low passage. High levels of footfall at the site from tourism also required a maximum cap of approximately 20 visitors at any one time, requiring staged visits for large groups. The availability of the captured site data and the development of mobile devices led to the development of the project to examine virtual access, a first application of the technology for HES.

The content of the app includes an annotated virtual tour (an explorable 3D model of the exterior of the tomb connected to the interior), a slideshow of images with text and a photorealistic-style rendered animation of the tomb with a cutaway showing its internal structure. Screenshots from the app can be seen in Fig. 82 and Fig. 83 with a sample of some of the content. The app ‘Explore Maeshowe’ is available for download on Android at the Google Play store and for iOS on Apple iTunes.

Fig. 82 Screenshot showing top-level menu of the Maeshowe app.





The Maeshowe lion

The "Maeshowe lion", or dragon, dates on stylistic grounds to just before 1150 AD. Its design combines Romanesque and late Viking features.

Fig. 83 Screenshot of the Maeshowe app showing information embedded in the 3D view of the interior.

To deploy the digital content, relevant HES staff were trained to use and present the content on mobile devices and VR headsets to visitors. This includes Orkney rangers, who can incorporate virtual access into tours and the presentation of the collection of sites that comprise the Heart of Neolithic Orkney UNESCO World Heritage Site. Feedback from the public has been positive; the app has proved useful in providing virtual access to the monument.

Working with the data, in 2016 the CDDV developed a VR experience using the full resolution interior imagery and geometric model in a high-end gaming setup, shown in Fig. 84. Developed with the HTC Vive headset, the demo allowed users to freely explore and walk around the tomb interior with tracked movement, and incorporated a handheld torch to provide a source of illumination and so make the experience more immersive.

Fig. 84 Maeshowe interactive VR experience used to explore the chambered tomb with a handheld torch.

3.4.3. Dissemination

The challenge of dissemination is to enable audiences and end-users to interact with and use digital documentation content, whether raw data or efficient polished 3D models. The required uses should be identified to ensure that the level of detail and information provided is not superfluous. Distribution of data or models should always aim for efficiency such as through sub-sampling at a resolution that is appropriate. Employing techniques such as 'decimation' for 3D models can retain surface details for areas of interest whilst lowering geometric detail in less significant areas (often planar topology). Lower resolution files will have a knock-on impact on file size and the performance of downloadable apps and web viewers. Whilst there is ever increasing internet bandwidth and higher speed connections, even via mobile roaming, there is still a need to present captured data in a format that is clear and well documented with metadata for the end-user.

Increasingly sophisticated methods for displaying 3D content on mobile and web-based viewers are being developed, in part due to developments in game engines and WebGL technology in tandem with GPU hardware. The repercussions of this is the ability to disseminate and make available higher resolution 3D files which would have been largely impossible a decade ago. However, content producers should account for the intended audience in terms of access and legacy hardware.

3.4.4. Augmented reality applications

Augmented reality (AR) combines 2D or 3D virtual objects and content with real-world images to present a composite view of the two. This is typically achieved through using computer vision algorithms to track the positional information of a physical (pre-specified) target in real-time. Tracking is maintained as either the device (usually a mobile device such as a phone or tablet) or the target move, enabling interactivity between the physical and virtual objects. This technique can allow a huge range of virtual content to be presented in an engaging and intuitive way. Fig. 85 shows an AR implementation of 3D model viewer, displaying a real-time 3D model of Rosslyn Chapel (created based on laser scanning and high-resolution photography) to let users explore the structure.

85

Fig. 85 Augmented reality application overlaying a 3D model of Rosslyn Chapel on top of a tracked 2D target.

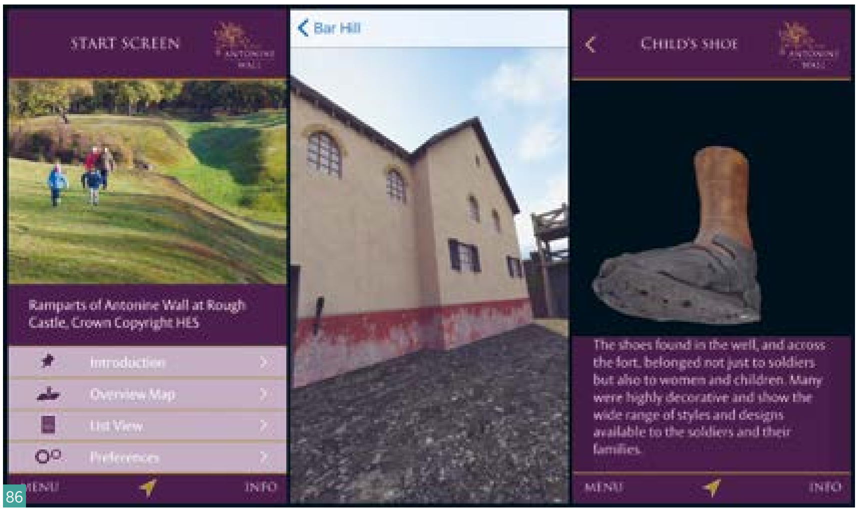
As a technique that often uses real-time 3D graphics on mobile devices, AR typically requires well optimised models, material shaders and texture maps. The quality of tracking depends on the robustness of the tracking algorithms and the legibility of the target, which should be clear and identifiable to the device camera under well-lit conditions. If the target is unrecognisable to the device, due to poor design or other impediments (e.g. distorted, partially covered, inadequate light) it is likely that tracking between the device and target will be lost.

This document includes a free augmented reality app for mobile devices, allowing readers to virtually explore 3D models of Rosslyn Chapel and the Nagasaki Giant Cantilever Crane cultural heritage sites. The 2D markers for the physical tracking of the models are included in the document appendices. Download our free Digital Documentation short guide companion app for Android and Apple iOS, search ‘Digital Documentation.’

3.4.5. Online and mobile access to digital resources for the Antonine Wall

As discussed earlier in section 3.3.6, data captured for the Antonine Wall as part of the Scottish Ten project was reused for the development of further digital interactive media. The wall itself comprises the northern most aspect of the collective cultural heritage site classified by UNESCO as ‘Frontiers of the Roman Empire World Heritage Site’ (FREWHS). To better disseminate information about the site in context and engage the public, a collaborative international project was launched comprised of Historic Environment Scotland in partnership with the CDDV, the Bavarian State Department for Monument Protection (BLfD) and Austrian firm Edufilm und medien GmbH. The outputs include a suite of mobile apps to be made available for free, which contain information and multimedia pertaining to the frontiers sites tied to maps and points of interest.

Fig. 86 shows screenshots from the Bar Hill application with examples of attached information. 3D digital assets were created as part of the reconstruction of Bar Hill Fort, which were reused for this site-visit informational app. In addition, 3D models of artefacts found at the sites through excavation were captured at local authority museums and The Hunterian museum. This served the dual purpose of enabling virtual access to the object collections for visitors using the app, and virtually ‘repatriating’ the artefacts which could be viewed within the context of the landscape in which they were excavated.



Ramparts of Antonine Wall at Rough Castle, Crown Copyright HES

The shoes found in the well, and across the fort, belonged not just to soldiers but also to women and children. Many were highly decorative and show the wide range of styles and designs available to the soldiers and their families.

86

Fig. 86 Screenshot from Antonine Wall interactive app showing 3D artefact model and layered information.

In addition to mobile applications, pre-rendered animations of the artefacts were made available via the project website in a rotating 'turntable' format, showing high resolution versions of the datasets which could be viewable by visitors without requiring the latest or higher-end mobile and computing hardware.

A novel aspect of the app functionality was to geolocate the video clips, text, images and 3D models. This enables the app to serve as an on-site interpretive guide, enriching visitor experience for members of the public using the free app on their phones or tablets. Using the phone's GNSS and compass with the 3D reconstruction of the fort, an augmented reality feature was enabled which positions and orients users in the virtual environment that corresponds to their geographical location on site (Fig. 87). This effectively overlays the reconstructed environment on the device and is enriched with further information.

87

Fig. 87 Mobile app used on-site at Bar Hill showing augmented reality overlay and (right) map of embedded geo-tagged information. Image courtesy of Sandra Walkshofer.

The project will continue to be developed for a further three years (officially 'Advanced Limes Applications') through European funding, with future app releases for additional sites on the Antonine Wall and a Roman fort in Bavaria. Collaboration between the project partners has allowed sharing of expertise and findings, and will continue to enable the creation and dissemination of learning resources which are aimed at engaging the various audiences.

4. CONCLUSION

This document has provided a synoptic overview of digital documentation of cultural heritage and some of the core techniques employed to non-destructively record, analyse and visualise sites and monuments. It also furnished examples of case studies where documentation's use has improved the care of the historic environment, promoted education, engaged audiences and informed research. It is intended to inform and guide a wide range of readers on these topics, but also present the limitations that accompany the techniques. As indicated in section 1.2, there are key considerations that should be taken into account before undertaking any scheme of digital documentation. These, we believe should pay dividends in the correct management, capture and delivery of potentially massive 3D datasets.

The nature of digital documentation is fast-paced development and evolving methodologies that reflect the technologies available. Innovation from global manufacturers and rapid product cycles drive the types of available capture techniques and tools able to handle or process the data. Scenarios often encountered in the historic environment such as condition monitoring present a challenge, where physical changes best observed over years, or even decades likely means changing equipment, survey tolerances, and data migration and potential obsolescence from file formats. Guidance and references to further reading on a range of topics within digital documentation are provided for more in-depth information on the relevant subject.

5. CONTACTS

Historic Environment Scotland
(Digital Documentation and Digital Innovation)
The Engine Shed, Forthside Way,
Stirling FK8 1QZ, UK
T: 01786 234 800
E: *digitaldocumentation@hes.scot*
W: *www.engineshed.scot*

Historic Environment Scotland
(General enquiries)
Longmore House, Salisbury Place,
Edinburgh EH9 1SH, UK
T: 0131 668 8600
W: *www.historicenvironment.scot*

Glasgow School of Art
(School of Simulation and Visualisation)
The Hub, Pacific Quay, Pacific Drive,
Glasgow G51 1DZ, UK
T: 0141 566 1478
E: *info@gsa.ac.uk*
W: *www.gsa.ac.uk/research/research-centres/school-of-simulation-and-visualisation*

Historic England
(General enquiries)
1 Waterhouse Square,
138-142 Holborn,
London EC1N 2ST, UK
T: 0207 973 3700
E: *customers@HistoricEngland.org.uk*
W: *www.historicengland.org.uk*

The Survey Association
Northgate Business Centre,
38 Northgate, Newark-on-Trent,
Notts NG24 1EZ, UK
T: 0163 664 2840
E: *office@tsa-uk.org.uk*
W: *www.tsa-uk.org.uk*

Royal Institution of Chartered Surveyors
12 Great George Street (Parliament Square),
London SW1P 3AD, UK
T: 0247 686 8555
W: *www.rics.org/uk*

Archaeology Data Service
Department of Archaeology,
University of York, The King's Manor,
Exhibition Square, York YO1 7EP, UK
T: 0190 432 3954
E: *help@archaeologydataservice.ac.uk*
W: *archaeologydataservice.ac.uk*

Digital Preservation Coalition
11 University Gardens,
Glasgow G12 8QQ, UK
W: *www.dpconline.org*

International Society for Photogrammetry and Remote Sensing (ISPRS)
W: *www.isprs.org*

Cultural Heritage Imaging
2325 3rd Street, Suite 323,
San Francisco, CA 94107, USA
T: +1 415-558-8672
E: *info@c-h-i.org*
W: *culturalheritageimaging.org*

BIM Task Group
W: *www.bimtaskgroup.org*

British Standards Institute
(General enquiries)
389 Chiswick High Road,
London W4 4AL, UK
T: 0345 086 9001
E: *cservices@bsigroup.com*
W: *www.bsigroup.com*

Scottish Futures Trust
15 Thistle Street,
Edinburgh EH2 1DF, UK
T: 0131 510 0800
E: *mailbox@scottishfuturestrust.org.uk*
W: *www.scottishfuturestrust.org.uk*

BIM4Heritage
W: *www.bim4heritage.org*

6. FURTHER READING

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7. GLOSSARY

Accuracy – How closely a measured value reflects the true value.

Albedo – The amount of light reflected vs. absorbed by a surface, often expressed as a percentage.

Azimuth – Angles measured clockwise from a reference meridian.

Cartesian (i.e. coordinate system) – A coordinate system that assigns two (for 2D space) or three (for 3D space) numerical coordinates for a point.

Checksum – An algorithm designed to create a unique code or string based on input data to detect difference between two datasets. Examples include Cyclic Redundancy Check (CRC), SHA or MD5.

CNC – Computer Numerical Controlled milling is a subtractive manufacturing process using a multi-axis tool following pre-calculated paths to create a physical representation of a 3D model with a high degree of accuracy.

Control – A stable frame of reference used to provide a baseline for measurements.

GSD (Ground Sample Distance) – The known real-world scale of an image pixel.

IMU (Inertial Measurement Unit) – A device used to measure forces and angular rate using a range of sensors such as accelerometers, gyroscopes and magnetometers.

LiDAR (Light Detection and Ranging) – The use of laser light to determine distance to an object or surface.

Manifold geometry – 3D model or mesh geometry that can be unfolded into a continuous flat piece. Non-manifold geometry includes topology with two or more faces that share a vertex but no edge, adjacent faces with no normals and three or more faces that share a single edge.

Mesh – In the context of 3D data, a mesh refers to polygonal geometry generated directly from point cloud data.

Nadir – Lowest point / direction directly below a position. Opposite of zenith.

Noise – Typically taken to either refer to either, (a) any extraneous data accidentally collected or generated during data capture, or (b) uncertainty component of a laser return signal, usually specified by manufacturers.

Orthoimage – Image geometrically corrected (“orthorectified”) such that the scale is uniform.

Point cloud – Group of discrete 3D data points, typically generated through spatial data capture.

Precision – How closely repeat measurements agree. Arithmetic precision refers to the total number of digits used to represent a Fig, e.g. number of decimal places.

Projection – In the context of mapping, the transformation of 3D coordinates onto a 2D plane.

RADAR (Radio Detection and Ranging) – The use of radio waves to detect objects or surfaces and determine their range or velocity.

Shader – An algorithmic instruction that governs the representation of a surface or 3D object and its response to lighting. May have adjustable parameters that depend on the type of shader.

Structure from Motion (SfM) – A photogrammetric technique that uses bundle adjustment algorithms to simultaneously calculate subject topology and camera position and orientation.

Topology – In the context of 3D models and meshes used to refer to the qualities of the surface geometry. ‘Retopologising’ refers to the creation of different geometric representation of a surface or object, often used in the context of cleaning or reducing polygonal/triangle count in 3D models.

Transformation – A mathematical operation to convert a dataset between coordinate systems.

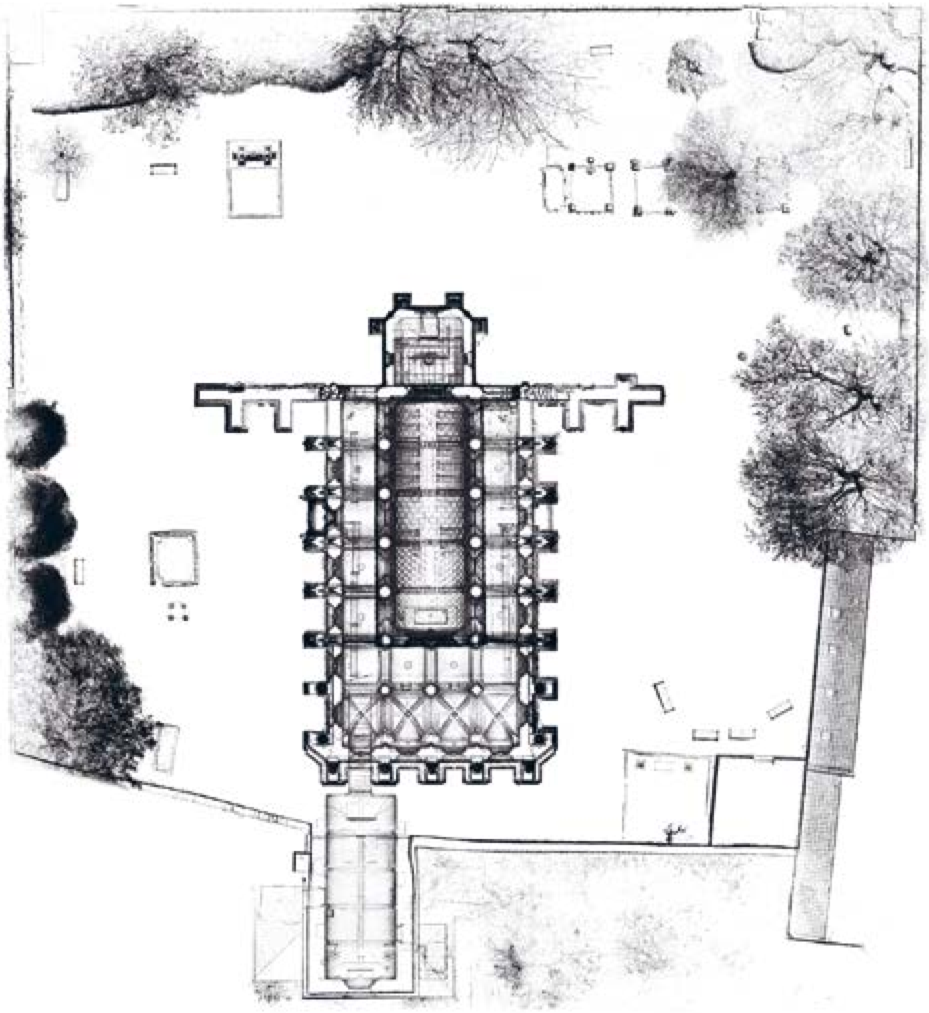
Zenith – Highest point / direction above a position. Opposite of nadir.

8. APPENDIX

8.1. Augmented reality app targets

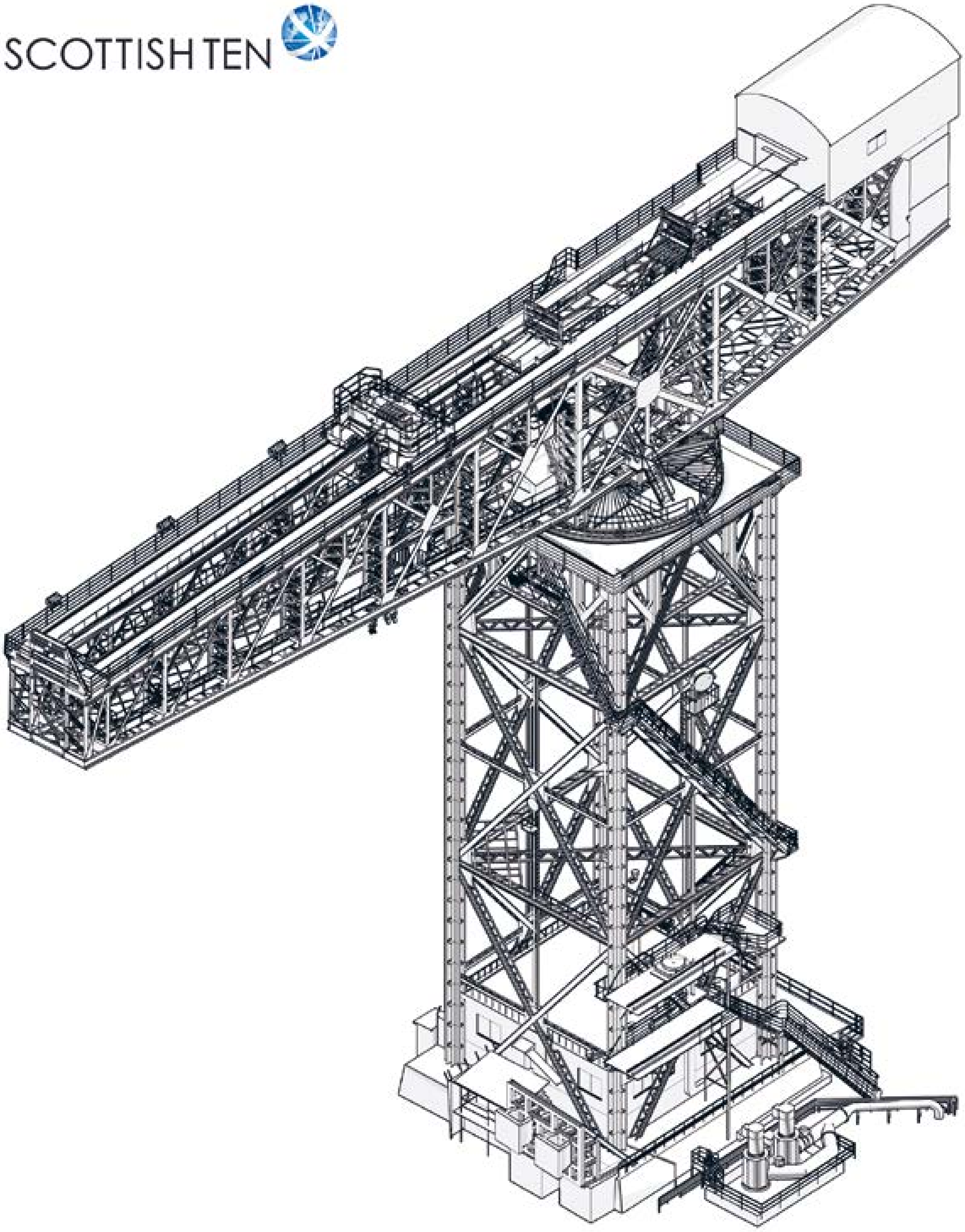
This document includes a free augmented reality app for mobile devices, allowing readers to virtually explore 3D models of Rosslyn Chapel and the Nagasaki Giant Cantilever Crane cultural heritage sites. These are the 2D markers for the physical tracking of the models. Download our free Digital Documentation short guide companion app for Android and Apple iOS, search 'Digital Documentation.'

ROSSLYN
CHAPEL 1446



CDDV

SCOTTISH TEN



CDDV
Centre for Digital Documentation and Visualisation

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MEIJI
INDUSTRIAL
REVOLUTION

内閣官房
Cabinet Secretariat

MITSUBISHI
HEAVY INDUSTRIES, LTD.
Our Technologies, Your Tomorrow

THE
ENGINE SHED
AN SEADA EINNSEIN

SCOTLAND'S BUILDING
CONSERVATION CENTRE

The Engine Shed

The Engine Shed is Scotland's building conservation centre. Based in Stirling, Scotland and run by Historic Environment Scotland it provides a home for technical conservation advice and engagement with the historic built environment. Open to visitors, and with a range of events and CPD learning opportunities, visit our website at *engineshed.scot* or contact us on *technicaleducation@hes.scot* to find out more.

Refurbishment Case Studies

This series details practical applications concerning the conservation, repair and upgrade of traditional structures. The Refurbishment Case Studies seek to show good practice in building conservation and the results of some of this work are part of the evidence base that informs our technical guidance.

All the Refurbishment Case Studies are free to download and available from the HES website *historicenvironment.scot/refurbishment-case-studies*

Technical Papers

Our Technical Papers series disseminate the results of research carried out or commissioned by Historic Environment Scotland. They cover topics such as thermal performance of traditional windows, U-values and traditional buildings, keeping warm in a cool house, and slim-profile double-glazing.

All the Technical Papers are free to download and available from the HES website *historicenvironment.scot/technical-papers*

INFORM Guides

Our INFORM Guides series provides an overview of a range of topics relating to traditional skills and materials, building defects and the conservation and repair of traditional buildings. The series has over 50 titles covering topics such as: ventilation in traditional houses, maintaining sash and case windows, domestic chimneys and flues, damp causes and solutions improving energy efficiency in traditional buildings, and biological growth on masonry.

All the INFORM Guides are free to download and available from the HES website *historicenvironment.scot/inform-guides*

Short Guides

Our Short Guides are aimed at practitioners and professionals, but may also be of interest to contractors, home owners and students. The series provides advice on a range of topics relation to traditional buildings and skills.

All the Short Guides are free to download and available from the HES website *historicenvironment.scot/short-guides*

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