Measured and Drawn

Techniques and practice for the metric survey of historic buildings (second edition)

ENGLISH HERITAGE

Measured and Drawn

"… so the Geometer, how excellent so ever he be,
leaning onely to discourse of reason, without practise
(yea and that sundrie wayes made) shall fall into
manifolde errors or inextricable Laberinthes."

Thomas and Leonard Digges, *Pantometria* 1571

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Techniques and practice for the metric survey of historic buildings (second edition)

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edited by Jon Bedford, Heather Papworth

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Preface

Measured and Drawn: techniques and practice for the metric survey of historic buildings is an introduction to the techniques used for recording historic places. Based on the experiences of practitioners working for English Heritage, it has been prepared as a guide to the widening variety of methods available in the production of documentation for conservation. The particular problems faced in applying the survey sciences to the art of recording are described as both theory and practice; this publication is for anyone undertaking recording and looking for help in choosing the appropriate techniques.

The publication of our *Conservation Principles: Policies and Guidelines for the Sustainable Management of the Historic Environment* (2008) has placed documenting and learning from decisions as a core principle with accessible records recognised as essential to the conservation process. The principles outline the need for adequate records in managing change to significant places. *Measured and Drawn* sets out to show how, through working closely with historians, conservators and archaeologists, such records are achieved by metric survey.

Updating *Measured and Drawn* has become necessary because, in the eight years since first publication, our knowledge of emerging techniques (in particular laser scanning) has strengthened and our understanding of the relationships between data capture technologies (categorised here as direct or indirect) has grown.

The interdependency of our questions about the historic environment and the techniques for the capture of data to answer them is complex. Metric survey is a primary tool in data capture that, managed correctly through brief and specification, enables heritage management to be effectively informed. These examples show how an appropriate response to information requirement is shaped by understanding the significance and value of heritage places, thus enabling the effective use of metric tools.

English Heritage has a rich resource in its valuable experience in applying metric survey, informing a wide variety of projects, from whole landscapes to individual structures. This collection of survey case studies is described from the viewpoint of the measurer and is unusual in that it describes the application of multiple, rather than single, techniques for conservation recording. Individual techniques are explored in more detail in our technical guide series, in particular: *Where on Earth Are We? The Global Positioning System in archaeological field survey* (2003), *Understanding Historic Buildings: a guide to good recording practice* (2006) and *3D Laser Scanning for Heritage: advice and guidance to users on laser scanning in archaeology and architecture* (2007).

The examples presented here reveal how heritage documentation is not simply a matter of solving measurement problems, but must also be informed by an understanding of the information needs and conservation management issues of our heritage places.

Edward Impey

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Summary

Measured and Drawn sets out to show how, through working closely with historians, conservators and archaeologists, optimum documentation can be achieved by metric survey. It explains how the balance between precision, cost and time when applying metric technologies to heritage documentation can be achieved by choosing an appropriate method and making sure project information requirements are understood by all from the start.

Measured and Drawn examines control, detail and procurement, and concludes with case studies of metric survey projects undertaken on historic buildings and structures ranging from Battle Abbey Courthouse to the nave ceiling at Peterborough Cathedral. It is prepared in sequence with *Where on Earth Are We? The Global Positioning System in archaeological field survey* (2003), *Understanding Historic Buildings: a guide to good recording practice* (2006) and *3D Laser scanning for Heritage: advice and guidance to users on laser scanning in archaeology and architecture* (2007) as part of an ongoing series of technical guides on heritage documentation.

The second edition is prepared in response to the publication of English Heritage's *Conservation Principles: policies and guidance for the sustainable management of the historic environment* (2008) which has placed documenting and learning from decisions as a core principle, with accessible records recognised as essential to the conservation process. The principles outline the need for adequate records in managing change to significant places.

Résumé

Measured and Drawn vise à montrer comment, en travaillant en collaboration étroite avec des historiens, des conservateurs et des archéologues, il est possible de réaliser une documentation optimale au moyen d'un relevé métrique. Il explique comment, avec l'application des technologies métriques à la documentation sur le patrimoine, il est possible de respecter un équilibre entre la précision, les coûts et les délais en choisissant une méthode appropriée et en veillant à ce que les exigences en matière d'informations du projet soient comprises de tous les intervenants dès le départ.

Measured and Drawn examine le contrôle, les détails et l'acquisition et se termine par des études de cas de projets de relevés métriques entrepris dans des bâtiments et structures historiques allant du palais de justice de l'abbaye de Battle au plafond de la cathédrale de Peterborough (nef). Il forme une séquence avec *Where on Earth Are We? The Global Positioning System in archaeological field survey* [Ou sommes-nous sur terre ? Le GPS dans les levés de terrain archéologiques] (2003), *Understanding Historic Buildings: a guide to good recording practice* [Comprendre les bâtiments historiques : guide des pratiques optimales d'enregistrement] (2006) *3D Laser scanning for Heritage: advice and guidance to users on laser scanning in archaeology and architecture* [Le balayage laser tridimensionnel : conseils et recommandations à l'intention des utilisateurs du balayage laser en archéologie et en architecture] (2007) dans le cadre d'une collection en cours de préparation de guides techniques sur la consignation d'informations relatives au patrimoine.

La deuxième édition est préparée en réponse à la publication par English Heritage de son ouvrage intitulé *Conservation Principles: policies and guidance for the sustainable management of the historic environment* [Les principes de la conservation : politiques et conseils pour la gestion durable de l'environnement historique] (2008) qui fait de la consignation d'informations et de l'enseignement tiré des décisions un principe de base, la mise en place d'une documentation accessible étant reconnue comme un élément essentiel du processus de conservation. Les principes décrivent la nécessité de consigner des informations appropriées lors de la gestion des changements de lieux importants.

Translated by Muriel de Grey in association with First Edition Translations Ltd, Cambridge, UK

Zusammenfassung

Measured and Drawn (Vermessen und eingezeichnet) führt detailliert aus, wie durch metrische Aufnahmen in enger Zusammenarbeit mit Historikern, Konservatoren und Archäologen eine optimale Dokumentation erzielt werden kann. Die Publikation erläutert, wie die Balance zwischen der gewünschten Genauigkeit, Kosten- und Zeitaufwand durch Anwendung von metrischen Technologien zur Dokumentation des Kulturerbes gehalten werden kann, indem die geeignete Methode gewählt und gewährleistet wird, dass die erforderlichen Informationen für das Projekt von allen Seiten von Anfang an richtig verstanden werden.

Measured and Drawn untersucht die Kontrolle, die Details und die Beschaffung und schließt mit Fallstudien von metrischen Aufnahmeprojekten ab, die an historischen Gebäuden und Strukturen vorgenommen wurden wie Battle Abbey Courthouse und das Kirchenschiff der Kathedrale von Peterborough. Die Publikation wird im Rahmen der Reihe *Where on Earth Are We?* (Wo auf der Erde befinden wir uns?) erstellt. *Das GPS (Global Positioning System) bei archäologischen Aufnahmen (2003); Verständnis historischer Gebäude: Ein Leitfaden für gute Aufnahmeverfahren* (2006) und *3D-Laser-Scannen für das Kulturerbe: Hinweise und Anleitungen für Anwender von Laser-Scannen in Archäologie und Architektur* (2007) als Teil einer laufenden Reihe von technischen Anleitungen für die Dokumentation des Kulturerbes.

Die zweite Ausgabe wird als Reaktion auf die Veröffentlichung der *Conservation Principles* (Grundsätze für die Erhaltung) des English Heritage vorbereitet: *Verfahren und Anleitungen für die nachhaltige Verwaltung der historischen Umwelt* (2008), die das Dokumentieren und Lernen aus Entscheidungen als Hauptgrundsatz festlegen, wobei zugängliche Aufzeichnungen für den Erhaltungsprozess als unabdingbar betrachtet werden. Die Grundsätze unterstreichen, dass angemessene Aufzeichnungen erforderlich sind, um Veränderungen an wichtigen Standorten zu verwalten.

Translated by Tamara Benscheidt in association with First Edition Translations Ltd, Cambridge, UK

Resumen

Measured and Drawn (*Levantamiento métrico y representación gráfica*) se propone demostrar que, en colaboración estrecha con historiadores, conservadores y arqueólogos, es posible capturar datos excelentes con el levantamiento métrico. El libro explica que se puede alcanzar el equilibrio entre precisión, coste y tiempo en la aplicación de las tecnologías de medición a la documentación del patrimonio cultural, con sólo elegir el método apropiado y asegurarse de que las personas involucradas en el proceso entiendan desde el principio los requisitos de información que implica el proyecto.

Measured and Drawn (*Levantamiento métrico y representación gráfica*) estudia el control, los datos y su captación, y aporta una serie de ejemplos de proyectos de levantamiento métrico realizados en edificios y estructuras históricas, desde la sala de audiencias de la abadía Battle hasta el techo de la nave de la catedral de Peterborough. El libro es el más reciente de una serie de obras entre las que también se incluyen *Where on Earth Are We? The Global Positioning System in archaeological field survey* (2003), *Understanding Historic Buildings: a guide to good recording practice* (2006) y *3D Laser scanning for Heritage: advice and guidance to users on laser scanning in archaeology and architecture* (2007), un grupo de guías técnicas sobre documentación del patrimonio cultural e histórico.

Las segunda edición se ha elaborado como complemento a la publicación de *Conservation Principles: policies and guidance for the sustainable management of the historic environment* (2008), del English Heritage. De entre todos los principios de conservación a los que se refiere su título, este libro destaca como fundamental la documentación y las lecciones que se pueden extraer de las distintas decisiones adoptadas y sostiene que la facilidad de acceso a los registros y archivos representa una parte fundamental del proceso de conservación. Los principios expuestos en esta obra subrayan la necesidad de disponer de registros adecuados para gestionar las modificaciones que se deban introducir en lugares de gran relevancia.

Translated by Elena Urena in association with First Edition Translations Ltd, Cambridge, UK

الخلاصة

يهدف كتاب "Measured and Drawn" إلى توضيح كيف يمكن تحقيق التوثيق الأمثل للآثار عن طريق المسح بالقياس المتري، وذلك عبر العمل بالتعاون الوثيق مع المؤرخين وعلماء الآثار وخبراء حفظ الآثار. كما يشرح الكتاب كيفية تحقيق التوازن بين الدقة والتكلفة وعامل الوقت عند تطبيق تكنولوجيات القياس المتري في عمليات توثيق التراث، وذلك عن طريق اختيار الأسلوب الأنسب وضمان أن جميع الأطراف المعنية بالمشروع تفهم متطلباته فهما واضحا من البداية.

ويتناول الكتاب بالدراسة عمليات التحكم، ووضع التفاصيل، وإدارة المشتريات، ويختتم بدراسات حالة لمشاريع المسح بالقياس المتري التي نفذت في السابق على عدد من المباني والهياكل التاريخية القديمة، والتي تتراوح بين مبنى قاعة باتيل آبي (Battle Abbey Courthouse) إلى مبنى سقف كاتدرائية بيتربورو (Peterborough Cathedral). وقد تم ترتيب الكتاب في تسلسل واضح: (1) أين نحن في العالم؟ - استعمال النظام العالمي لتحديد المواقع في المسح الميداني للمواقع الأثرية (2003)، ثم (2) فهم المباني التاريخية : دليل الممارسات الجيدة في مجال تسجيل المواقع الأثرية (2006)، وأخيرا (3) المسح ثلاثي الأبعاد للمواقع التراثية: توجيهات ونصائح لمستخدمي المسح بالليزر في مجالي الآثار والعمارة (2007)، وذلك كجزء من سلسلة متواصلة من الأدلة التقنية المتعلقة بتوثيق التراث.

وقد تم إعداد الطبعة الثانية من الكتاب استجابة لقيام هيئة التراث الإنجليزية بنشر تقرير بعنوان: "أسس حفظ التراث: سياسات وتوجيهات من أجل الإدارة المستدامة للبيئة التاريخية" (2008)، حيث تم وضع التوثيق والتعلم من القرارات السابقة في صميم أسس العمل، مع اعتبار توفر السجلات التي يسهل الاطلاع عليها عنصرا ضروريا من عناصر عملية حفظ المعالم التراثية. كما تسلط هذه الأسس الضوء على ضرورة الاحتفاظ بسجلات وافية ضمن عملية إدارة عملية تغيير المواقع التراثية الهامة.

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摘要

《古迹测绘》（Measured and Drawn） 一书展示了在度量测量活动中，如何通过与历史学家、古迹保护学家、考古学家的密切合作来制作最佳古迹测绘文献。本书介绍了在使用度量技术制作古迹文献时，如何通过选定适宜的度量方法，并在项目伊始让所有参与方充分了解项目资料要求来获得精确度、成本和时间三者之间的平衡。

《古迹测绘》详细介绍了项目控制、细节和采购，并在最后分享了一些历史建筑度量测量的案例，如Battle Abbey Courthouse和Peterborough Cathedral中庭天花板测量项目。本书是继《我们到底在哪儿？考古实地测量中全球定位系统的应用》(Where on Earth Are We? The Global Positioning System in archaeological field survey)(2003)、《了解历史建筑：优良记录实践指南》(Understanding Historic Buildings: a guide to good recording practice)(2006)和《古迹3D激光扫描：给考古建筑激光扫描使用者的建议和指南》(3D Laser scanning for Heritage: advice and guidance to users on laser scanning in archaeology and architecture) (2007)之后，古迹文献技术指引丛书的又一新作。

本书第二版的面市是对英格兰古迹委员会先前出版的《古迹保护原理：历史环境可持续管理的方针和指引》(Conservation Principles: policies and guidance for the sustainable management of the historic environment) (2008)一书的响应。该书认为文献记录和决策学习是古迹保护的核心原理，可取得的记录是古迹保护过程的关键环节。这些原理所阐述的是：详实的记录对于管理重要古迹的变化是很有必要的。

Translated by Cheng Ma in association with First Edition Translations Ltd, Cambridge, UK

概要

『Measured and Drawn (測量と製図)』は、歴史学者、保存修復専門家、考古学者との密接な協力の下に、いかにすれば測量を通じて最適な文書資料を作成できるかを詳述する書である。内容としては、測量技術を応用して文化財の資料を作成する際に、適切な方法を選択し、プロジェクト情報に求められるものを全員が最初から確実に理解することによって、精度とコストと時間をバランスのとれたものとするための方法について解説する。

『Measured and Drawn (測量と製図)』は、バトル・アビーのコートハウスからピーターバラ大聖堂の身廊天井にいたるまで、歴史的建造物で実施される測量プロジェクトについてその監督・細部・周旋を考察するとともに、ケーススタディを通して結論を導く。文化財の資料作成に関する専門書シリーズとして、『Where on Earth Are We? The Global Positioning System in archaeological field survey (我々は一体どこにいるのか?考古学分野測量におけるグローバル・ポジショニング・システム)』(2003年)、『Understanding Historic Buildings: a guide to good recording practice (歴史的建造物を理解する:優れた記録作業を行うための手引き)』(2006年)、『3D Laser scanning for Heritage: advice and guidance to users on laser scanning in archaeology and architecture (文化財の3Dレーザースキャン:考古学・建築学でレーザースキャンを利用する際の助言と手引き)』(2007年) の順に編纂されている。

第二版は、入手可能な記録文書を保存修復プロセスに欠かせない重要なものとみなした上で資料作成と決定に基づく学習を原則の中核に据えるイングリッシュ・ヘリテージの『Conservation Principles: policies and guidance for the sustainable management of the historic environment (保存修復の原則:持続可能な歴史的環境管理の方針と手引き)』(2008年) の出版に伴い編纂されたもの。原則を通して、重要な建造物等に加えられる変更管理における適切な記録の必要性を概説している。

Translated by Kumi Unno in association with First Edition Translations Ltd, Cambridge, UK

1 Introduction

1.1 Why use metric survey?

Human memory and perception are not perfect. Detecting change and informing actions is rarely possible without measurement or precise information. Choosing a method to meet the needs of research, analysis and conservation must consider the value of measurement in the record. It is true that good records can be made without recourse to measurement (for example sketches, photographs and written descriptions). It is when the different components of a conservation team need to work together that a common metric data set is needed and measurement becomes a key link in the conservation cycle. Metric survey can be used by a variety of specialists. For example, a photogrammetric survey that is acquired in the evaluation phase may be subsequently plotted for mapping condition, later used for facade repair scheduling and then archived and used as a pre-intervention record.

To use an appropriate technique it is essential to understand its performance, the precision expected and the resources available. There is no simple formula that will determine which survey technique might be most appropriate in any given situation. There is, however, a relationship between the scale required, the selection of data and the desired output. If the object is small and relatively few points need to be recorded to describe it (eg a single block or brick) it can be measured by hand, but for the entire facade of a building a mass capture method would be more appropriate. Simple measurement methods are not likely to be suitable if objects are large, complicated or require multi-purpose data sets in a short time span. Ultimately the suitable application of technique is a balance between the anticipated end use of the survey, the precision required and the availability of resources.

The surveying of our heritage estate is a crucial part of our role in caring for it. Metric survey forms the base map upon which our conservation actions are planned and recorded; mapping the historic environment helps us to understand, manage and enjoy it. 'Metric survey' is the term used to describe the application of precise, reliable and repeatable methods of measurement for heritage documentation. Survey in general, and metric survey in particular, follows conventions that influence the selection and presentation of measured data. It is hoped that the examples shown here will reinforce the necessity of respecting the conventions that have served architecture so well for the optimum transmission of information.

1.1.1 The heritage cycle and heritage documentation

The heritage cycle describes societal engagement with the historic environment in terms of understanding, valuing, caring and enjoyment. This cycle triggers conservation actions at the understanding and caring phases, and heritage documentation is an integral part of the conservation process. It is essential because it provides the data for understanding significance and recording condition, interpretation and action. Because the heritage cycle and its dependant conservation actions are continuous processes, heritage documentation is also a continuous process enabling the monitoring, maintenance and understanding needed for conservation by the supply of appropriate and timely information.

Article 16 of the Venice Charter of 1964 set out the responsibilities of those charged with understanding and caring for the historic environment to ensure that 'in all works of preservation, restoration or excavation, there should always be precise documentation in the form of analytical and critical reports, illustrated with drawings and photographs. Every stage of the work of clearing, consolidation, rearrangement and integration, as well as technical and formal features identified during the course of the work, should be included. This record should be placed in the archives of a public institution and made available to research workers. It is recommended that the report should be published.'

Documentation is both the product and action of meeting the information needs of heritage management. It makes available a range of tangible and intangible resources, such as metric, narrative, thematic and societal records of cultural heritage. Survey is a key aspect of heritage documentation as recognised by the International Council on Monuments and Sites (ICOMOS) general assembly at Sophia in 1996: 'Recording is the capture of information which describes the physical configuration, condition and use of monuments, groups of buildings and sites, at points in time and it is an essential part of the conservation process.'

The needs of the conservation process will require re-examination of the metric record at the monitoring and re-evaluation stages. This means that survey data must be archived in anticipation of future uses beyond the immediate.

1.2 Metric survey techniques

Metric survey involves the use of precise and repeatable measurement methods to capture spatial information. The acquisition of the right survey for the right cost at the right time is a process that requires an appreciation of the balance between the three key elements of the survey process:

Selection
Measurement
Communication/presentation

The interaction between the surveyor and the subject of the survey is a process that influences the information we collect from the historic environment. In metric survey this process is typically controlled by a brief and specification rather than by the inquiry driven concerns of thematic investigators.

1.2.1 Types of metric survey

Metric survey techniques can be divided into two groups: indirect and direct.

Indirect techniques (such as photo-grammetry and laser scanning) are used when there is a need for undifferentiated metric data or when the size of the subject and its scale of representation require a high density of point capture. The primary data sets from indirect techniques are largely free of data differentiation other than that imposed by the constraints of the capture method itself. As undifferentiated data, the products of indirect techniques will need to be processed, and it is in this post-capture phase that the selection and presentation of information needs to be controlled. Indirect techniques need careful planning to maximise their benefit. The purpose of data acquisition must be apparent to all in the information processing path from capture to presentation.

Since the late 1850s there has been no dispute over the merit of the controlled stereo photograph as a primary ante-disaster tool: the restitution of displaced material by anastylosis is massively improved with the use of ante-disaster stereo records. The acquisition of ante-disaster data sets has long-term benefits that cannot be overlooked when making assessments of risk to valuable and irreplaceable historic fabric. The ante-disaster performance of indirect techniques is compromised if recorders fail to understand the significance and value of the subject. Indirect techniques provide mass data capture within a time-scale unmatched by direct techniques and the failure to deploy them when appropriate may result in an unnecessarily high expenditure of resources.

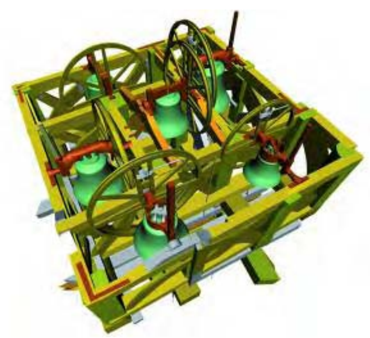


Fig 1
Model enabling a hidden structure to be seen: by recording in 3-D the bell frame can be displayed to show its construction and development from a measured data set.

Direct techniques – such as using a Total Station Theodolite (TST), Global Positioning System (GPS) or measured drawing – are selection driven at capture and dependant on the surveyor's skill at implementing information requirements during the measurement phase. Observational skills, competence in survey and clarity in the purpose behind the survey are especially important for successful outcomes when using direct techniques. Direct techniques do not have the flexibility of indirect methods because of their differentiated nature. They are highly effective at meeting the thematic focus of many recording tasks (Fig 1) as they maximise the expertise of a specialist in the field, they are rapid, they minimise post-capture processing and they convey domain specific information efficiently.

1.3 Key concepts

1.3.1 The survey brief

The desired outcome of a survey project is achieved as a partnership between the surveyor and the survey user's requirements of the survey. A clear statement of the selection criteria and presentation standard expected is essential. The brief and specification are all that guide the survey to the right documentation outcome. Preparing a brief with clearly defined survey requirements is far better than appointing a surveyor and hoping for an appropriate outcome.

The end uses of survey data are diverse and may include monitoring, project planning, stylistic analysis, ante-disaster records, condition records and intervention plans. A short statement of why a survey is needed will help a correct decision on the method of data capture which is required for optimum data usability.

1.3.2 Reconnaissance

Familiarity with the site, the purpose of the survey, its conditions and constraints are essential parts of planning any survey. The better informed the surveyor the better the outcome. No survey should begin without consideration of previous survey work and an appraisal of the site, its conditions and the practicalities of getting a survey done. Preparation of a reconnaissance report is often worthwhile and the opportunity to discuss the brief in the light of site knowledge is valuable should the expected method prove difficult to employ.

1.3.3 Scale

When measured data is transmitted it is shown as a scaled representation of what was surveyed. It is a common misconception that when survey data is viewed in a Computer Aided Design (CAD) system it is 'scale free'. This can never be the case, because the survey data is necessarily an abstraction: its very purpose is to transmit selected information. Surveys are always expected to be undertaken and subsequently used with a given scale in mind: a survey should never be presented over-scale without a clear statement that this is so, because the metric performance of the information is compromised. Scale is crucial to the performance of survey data as different information is recorded at different scales. Understanding the constraints of scale is vital to making appropriate use of survey data.

1.3.4 Precision and accuracy

In surveying, it is common to use the terms 'precision' and 'accuracy' to describe the performance of data; it is important to make the distinction between the performance of a measurement system and the performance of a survey as a whole. When working with metric data the performance of both the method used and its provenance should be understood, as the purpose of a survey influences the selection and presentational criteria used as well as the method of measurement.

Precision describes the degree of mutual agreement or repeatability among a series of individual measurements, values, or results. The precision of measurement is a function of both the definable precision of the object being measured and the measurement technique used. If an object is measured several times, by different operators, using the same technique and the differences recorded and the same procedure is repeated with a different object, the variation in object precision and measurement performance can be assessed.

A test of the accuracy of survey work describes how near a single recorded value is to the 'true' value or the degree of conformity of a measured or calculated quantity to an actual, standard, nominal or absolute value. The order of accuracy may be determined as:

- relative, where comparison to an internal reference is used;
- absolute, where a reference value is known with certainty;
- nominal, where an average is used as the reference;
- inner, where the measurement system alone is described; and
- outer, where procedural factors are included.

Great care should be taken when using the terms precision and accuracy: it is wise to carefully identify and qualify specific aspects of survey work when using them. If a survey is required to be precise and accurate it is better to say why and how.

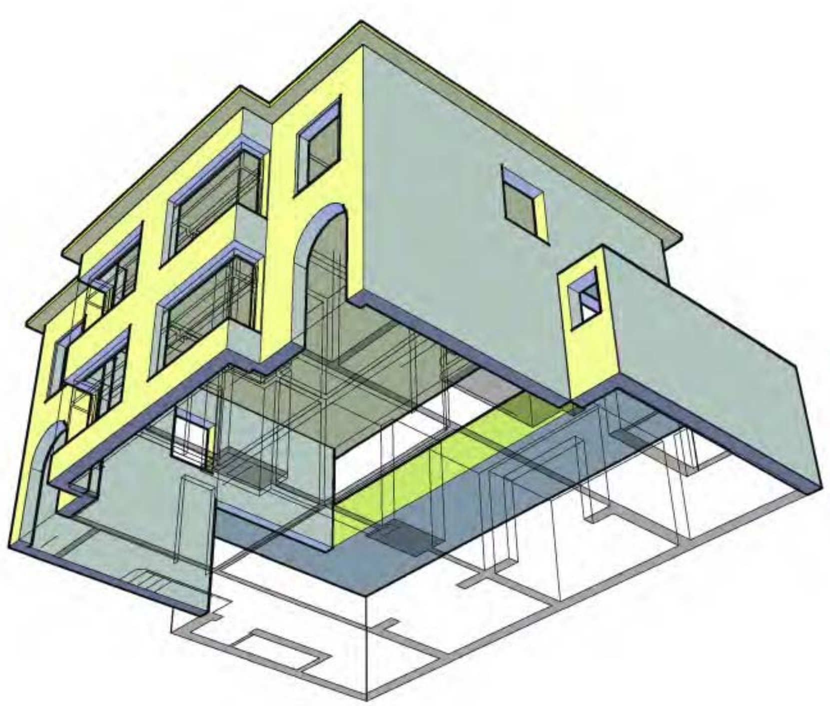
1.3.5 Control

To achieve consistent and robust results the surveyor must be able to demonstrate the actions taken to minimise error. Without a rigorous framework of high order measurement the information captured cannot be joined together into a metrically reliable whole. Control procedures will vary according to the survey method deployed but will always be required; there should be no action without control. Control, like survey in general, will be dependant on the required scale and the method chosen. The overriding principle is that a higher order of precision is achieved and recorded for a network of points from which lower order work can be tied together.

1.3.6 Projection: plan, section and elevation

Most survey methods today capture 3-D data, but this is usually presented for end use in 2-D. The presentation of 3-D information on 2-D media is an abstraction that drives many graphical conventions and standards. A projection represents a 3-D surface on a 2-D plane. In map making the projection deals with the curvature of the earth (it is very important in techniques like GPS surveying). Architectural drawings use a 'square on' or orthographic projection to achieve the conventional views of plan, section and elevation.

Fig 2
A plan is a 2-D representation of a building as seen from above. The ground floor plan is like the 'footprint' of the building; it is the key to understanding its function.



A plan is similar to a conventional 'map' of a space. It is a view looking down from above projected onto a horizontal plane cutting through the building at an agreed height (usually between the waist and shoulder for each floor) to show the functional openings of the building (Fig 2).

A section is a vertical cut through a building to show its internal spaces projected onto a vertical plane. Sections may also show the revealed inner surfaces of the building (known as sectional elevations).

Elevation describes a view of the vertical faces (facades) of a building. The conventional viewpoint is taken perpendicular to the building with a vertical plane of projection.

1.3.7 Integration of techniques

Few buildings are surveyed using a single technique. A number of techniques, both direct and indirect, are commonly deployed and the data integrated to obtain a finished survey. The integration of data from different sources relies on a common control system being used and, usually, CAD as the data integration platform. For example, site sketches of key details and photographs showing layout, finishes, and material types are essential to supplement TST or GPS survey. The generation of data with both architectural sensitivity and metric performance requires investment in both traditional drawing and CAD skills. CAD brings the benefit of a platform in which a variety of data types can be brought together for drawing production.

1.3.8 Economy of effort

The communication of captured information to agreed standards requires an understanding of the effectiveness of a given technique when constrained by a survey requirement. Many surveys, despite excellent metric performance, fail because the client has expected a particular method of depiction of a given subject and cannot use the survey for its intended purpose. The balance between precision, cost and time when applying metric technologies to heritage documentation should be considered carefully when commissioning survey. If the technique deployed is inappropriate the project will suffer either through inadequate data or through the extra costs of repeating the survey tasks. Successful documentation depends on the interaction of the principal specialists involved: if the survey is driven by a clear understanding of its purpose it will form a sound basis for conservation action; it must therefore be informative, accessible and legible.

1.4 Principles of verifiable survey

There are three basic principles guiding survey:

1 'No action without control.'
Survey should not be conducted without consideration of how the parts will fit together.
2 'Work from the whole to the part.'
Establish the geometry of the widest area of interest before tackling detail in a small area.
3 'Match the order of precision and scale to the time and resources available.'

Survey is constrained by the scale of the required outputs and the costs of both capture and presentation.

Survey procedures are characterised by:

- Systematic data logging and processing, with sufficient metadata to allow an independent check.
- Repeatability: Measurements cannot be unique to a given record. Others should be able to achieve similar results using similar techniques.
- Verification: The retention of raw unprocessed measurement data as a demonstration or proof of survey.
- Transparent data provenance: If a survey is reliant on unique expertise (for example the selection of lines in a drawing) the qualification and experience that guarantees that knowledge should be declared in the method statement and declared in the authorship of the work.

2
Control

2.1 Introduction

Survey requires a network of fixed points at a high order of accuracy, so that detail measurements derived from them will be consistently precise. The preparation of rigorous control data is a costly but essential part of the survey process. Any proposal for survey should include a description of the control technique proposed and its expected accuracy. Control measurements underpin the precision of the whole survey, so control data will be determined to a higher order of precision than that used for detail. A TST is an ideal tool for the control of small to medium sized sites (*c* 50m² – 500m²) as it is precise and flexible. Using methods like traversing, the precision of computed positions is raised above that of radial detail shots. Although most control for building survey is undertaken using a TST, GPS can supply data to high orders of precision for larger sites (*c* 500m² – 5000m²), but its application in building survey is restricted by the need for a clear view of an open sky. Control methods are often specific to particular survey types, scale and speed of work.

Prior to establishing control on any site it is essential to plan the work. Undertaking a thorough reconnaissance helps to avoid committing equipment and resources to positioning stations or control points fruitlessly. Control requires:

- robust geometry;
- careful measurement;
- an appropriate distribution of stations/control points;
- that an appropriate method has been chosen;
- that witnessing diagrams should be provided to permit others to locate either stations or control points and re-occupy stations at a later date;
- that station markers and control points should be placed where they won't be disturbed;
- that stations be positioned where equipment will be out of harm's way during survey work;
- that the co-ordinate system is appropriately orientated as agreed with the project team; and
- that personnel should be appropriately trained.

2.2 Simple control for measured drawing

Room plans are commonly constructed by plotting a braced figure formed by the taped diagonals and the side lengths (Fig 3). Unless great care is exercised the plan of a large building comprising many rooms on several floors should not be attempted without a series of reliable control points linked together by a traverse (*see* section 2.3). The plans of small buildings can be rapidly controlled by triangulation. It is extremely important to book the distances clearly and consistently on a site drawing to ensure that the room geometry can be reconstructed. Developing the skills needed to guide the selection of lines and the geometry to plot them is essential. The examination of the building, needed to determine its lines on a drawing, is a helpful procedure for understanding both the building and its layout.

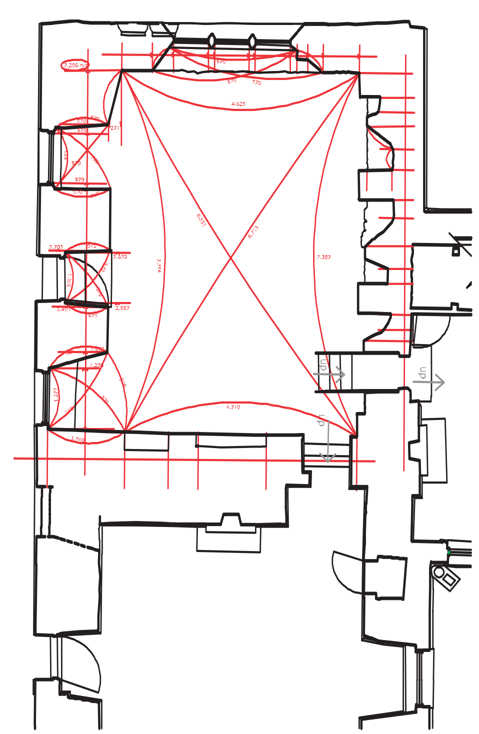


Fig 3
Measured survey note showing taped wall lengths and diagonals used to control the geometry of a building.

2.2.1 Baselines

A drawing of a single wall or window may not need elaborate and costly control. A horizontal level line (datum line) may provide sufficient control for a single elevation drawing. This can be a chalk or fixed string line across a wall. This line can be used as a base for offset measurements either above or below it. Linking datum lines together by using plumb lines to resolve the transfer of horizontal measurements can successfully control a facade. A baseline can be established as a reference for plotting detail for plans and triangulation can be used to link baselines together. Whole drawings can be made from these kinds of simple control: for the drawing of a single elevation a plumb line and a datum line may be sufficient. While a baseline can provide control for a single elevation, it will be unrelated to other survey on the site unless it is linked to a common control system. To relate separate elevations together, at least three points on each elevation will need to be related to a common control system.

2.3 Instrument control

For precise work a control system of fixed points is essential. A competent surveyor should be able to establish a network of control points on a site rapidly and precisely. Agreement should be sought as to the siting of stations, as the ideal position for a control station will be one in which robust control geometry is achieved, while also being suitable for measuring the subject of the survey. A competently used TST is ideal for this provided that:

- the instrument is in good order;
- the survey team are appropriately trained;
- the instrument is correctly centred;
- observations are made and recorded carefully;
- station and control point markers are correctly used;
- the chosen instrument is used within its design capacities; and
- sufficient equipment and personnel are available.

2.3.1 Traverse

The purpose of a traverse is to establish a co-ordinate system to locate points relative to each other in a common co-ordinate frame. A traverse requires an identified starting point and an orientation. There are several ways to obtain the starting data, and surveyors should make an effort to use the best data available to begin a traverse. Data may be:

- available in the form of existing stations (with the station data published in a list or schedule);
- related to the National grid (established by GPS); and
- arbitrary (for a survey divorced from the national grid or existing control network).

2.3.2 Open traverse

An open traverse originates at a starting station and proceeds sequentially to its destination, ending at a station with an unknown (or unfixed) position. The open traverse is the least desirable traverse type, because it does not provide the opportunity for checking the accuracy of the fieldwork. The distribution of error cannot be achieved without a comparative or fixed value for the end position; without a check, the precision of station positions is poor. Therefore, the planning of a traverse should always attempt to provide for closure of the traverse.

2.3.3 Closed traverse

A closed traverse (Fig 4) either begins and ends on the same point (a loop traverse), or begins and ends at points with previously determined and verified co-ordinates (a link

Fig 4
A closed loop traverse at the Church of St Laurence, Priddy: the angles and distances forming the sides of the polygon are rigorously observed and the station positions adjusted to distribute the accumulated error in the measurement of angles and distances. The station positions are thus calculated to a high order of precision.

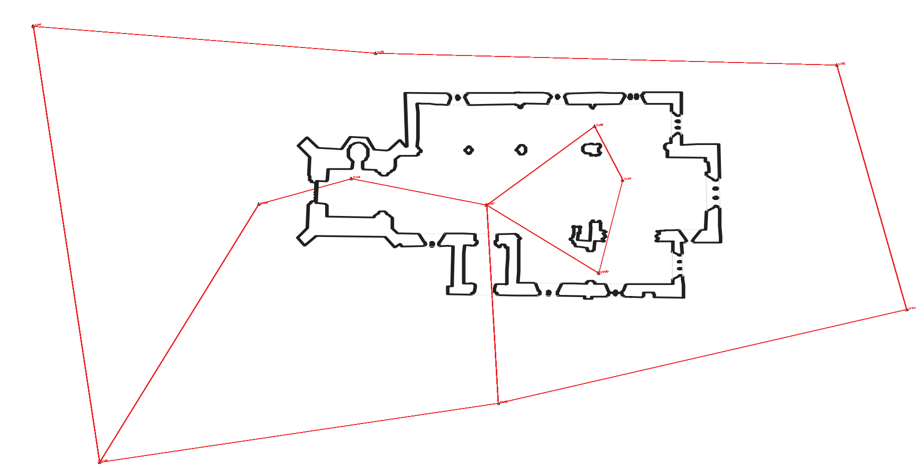


Fig 5 The construction of a six-station traverse: the distances and angles are measured in sequence to generate rigid geometry with provable precision. Each station is occupied, and the angles and distances formed between it and two other stations observed. The polygon is closed by occupation of the station at the closing angle.

traverse). In both cases, the angles can be closed and closure accuracy can be mathematically determined.

Loop traverses are commonly used for the control of small sites. The loop passes around the perimeter of the site with stations sited so that radial detail shots are also possible or so that spurs can be set out to cover detail work with the minimum number of additional stations. Closing a loop through a building is difficult and stations inside buildings are usually placed as a link traverse between two stations on the external loop.

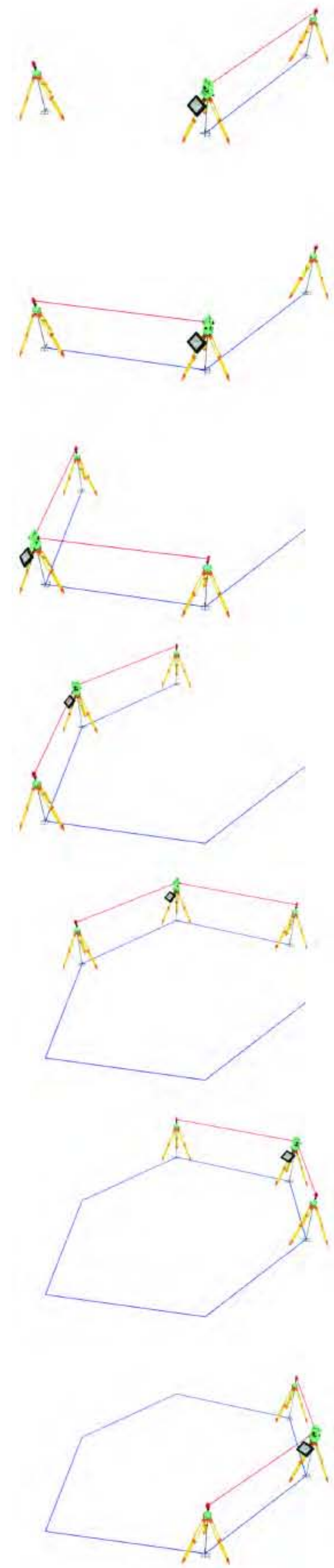
2.3.4 Traverse procedure

It is good practice to reconnoitre a site for traverse stations in advance. The stations must be located so that they are inter-visible. The number of stations in a traverse should be kept to a minimum to reduce the accumulation of error and the amount of computation required. Short traverse legs (sections) require the establishment and use of a greater number of stations and may cause disproportionate errors in angular measurement. Small errors in centring the instrument, in station-marking and in instrument pointing are magnified and are reflected in the traverse misclosure.

Station markers need to be securely fixed. They must be clearly marked with the centre point to designate the exact point of reference for measurements. To assist in re-occupation, preparation of a reference document (witness diagram) is essential. This shows the station location relative to a minimum of three points of detail that are likely to survive. When working in heritage places it is important to consider the impact of survey marks on the fabric of the monument.

The traverse procedure should be undertaken with a traversing set comprising a minimum of three tripods, three inter-changeable tribrachs, two matched prisms and a TST.

The measurement phase of a traverse proceeds by setting up the instrument over the starting station point, with a prism over a second known point and another prism over the first new station (Fig 5). These three stations are known as the occupied (current), the rear (back or RO), and the forward (fore). The occupied station is the station over which the instrument is set. The back station is the station that is either a point to which the



azimuth is known or the last occupied station. The fore station is the next station in succession. On occupation of a station the instrument height is recorded and the angles and distances between the back and fore stations are measured and recorded.

Measurements should be repeated according to the precision requirement. The simplest method of resolving traverses will require a computed horizontal distance to derive 2-D co-ordinates for the station values: be aware that most survey instruments measure a slope distance. A correction for slope is applied if the vertical angle, height of instrument and height of target is recorded for each shot.

The number of personnel available to perform survey operations depends on the resources available and the size of the territory to be covered. A small traverse can easily be undertaken by one surveyor but over larger sites an assistant will be useful for moving targets or guarding tripods. There are two main tasks required for traversing.

Instrument operation:
The instrument operator measures the angles (both horizontal and vertical) and the distances from each traverse station. The data is recorded on a tabulated record sheet, within the instrument or onto a separate data logger.

Setting out and minding targets:
This involves marking and witnessing the traverse stations, removing the target from the rear station when signalled by the instrument operator, and moving the target forward to the next station.

Traverse observations must follow a consistent procedure. The angles should be turned in the same direction and taken in sets. A round of angles describes the turning of the horizontal angle and a 'set' is the data from at least two rounds, one taken on each face of the instrument. Using both faces of the instrument distributes errors in centring. At each set up the surveyor should make sure the angles are booked securely and check the sets are complete (including the instrument and target heights) before moving on. If the traverse is manually booked, make use of a prepared observation form so that each angle and distance is recorded so that it can be clearly identified with the occupied station, target stations and the heights thereof.

The loop is completed when the closing set of measurements is taken, at the re-occupation of the starting station. An approximate check of the misclosure of the traverse should be obtained as a check on missing data before finishing fieldwork, as recovering missing measurements once off site is often not possible.

On completion of the measurement phase, the traverse data is adjusted so that the precision of the co-ordinate values for each station is optimised, based on the best possible error distribution. Traverse adjustment is based on the assumption that errors have accumulated systematically throughout the traverse. The correction is distributed proportionately among the angles and distances of the traverse.

2.3.5 Accuracy and performance

The performance of control data must be known for it to be useful, because the precision of all subsequent survey tasks relies on the co-ordinate values derived from it. The overall accuracy of a traverse depends on the equipment, on the procedures used in the measurements, and on the accuracy of the starting and closing data. A correctly computed traverse has a statistically proven precision, but it is only as good as the collected data: failure to maintain a robust measurement procedure will inevitably result in errors that will compromise the quality of the control data.

An accuracy ratio or part error of 1:5000 is the minimum accuracy sought in topographic surveying. For horizontal distances, an accuracy of at least 2mm per 100m must be achieved. The part error represents the traverse accuracy and, once obtained, can then be benchmarked against established standards and specifications. If it does not fall within allowable limits, the traverse must be re-done.

2.3.6 Resection

Resection involves the computation of instrument position via observation of two or more reference marks or stations of known position (Fig 6). A set of reference marks can be placed in the area to be surveyed and observed from the current instrument position. Once the instrument has been moved to a new position, these marks can then be re-observed to determine the new station co-ordinates. Resections work well provided that:

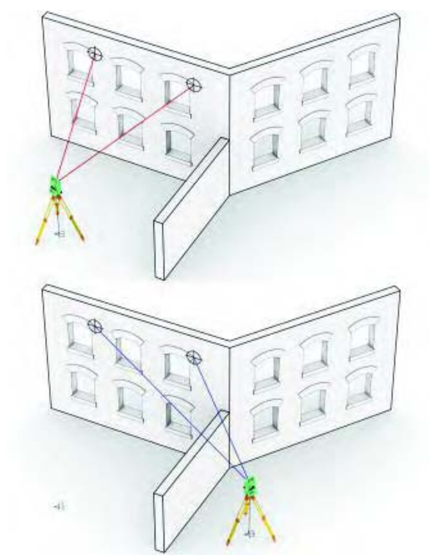


Fig 6
Resection as local control in building survey: by solving a series of linked triangles control can be transferred around a building quickly, particularly if using REDM so that facade targets can be easily measured. In this example the obstruction of the wall is cleared by placing reference points on the facade for observation from the other side of it.

- targets are carefully chosen for reflectance;
- angles are well conditioned;
- reference positions are clearly marked; and
- obliqueness to the target point is avoided.

Deriving control positions based on multiple resections should be avoided.

2.3.7 Two-point intersection

Two-point intersection (Fig 7) is a technique that uses the solution of triangles measured by angle only from a baseline of known length. Intersection is commonly used for photogrammetric control where targets are attached to a facade. Two stations are set up at either end of a baseline approximately parallel to the subject (usually also forming part of a traverse, in order to link the control points to the local co-ordinate frame). Horizontal and vertical angles are measured to each of the targets from both of the stations with sets of multiple instrument readings to improve precision. By measuring multiple triangles from the same base the position of the facade points are calculated: each point is fixed by a triangle with one known side and two angles.

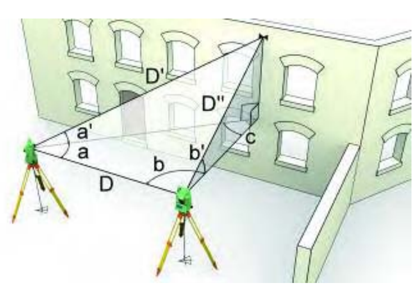


Fig 7
Two-point intersection: used for obtaining the coordinates of 3-D points to a high order of precision, in order to control targets or detail points on stereo photographs. The angles a, a', b and b' plus the distance D make it possible to calculate D' and D", and thus the co-ordinates of the target.

2.4 GPS

Where there is a requirement to locate the survey on the national co-ordinate system, GPS, when used with appropriate equipment, can supply Ordnance Survey National Grid (OSNG) control data quickly and easily. There are four considerations to address when using GPS:

1 The need to have a clear view of the sky in order to receive satellite signals.
2 The different orders of point precision when compared to positions computed with a TST.
3 That collecting reliable data requires both survey skill and specialist training.
4 That survey grade GPS equipment is costly.

These considerations effectively restrict the use of GPS for building survey to the linking of two or more exterior control stations to the National Grid (to establish position and orientation) and to ensuring that surveys of different buildings over a wide area are in a common co-ordinate frame.

3
Metric survey techniques

By using the broad classification of metric survey techniques as either direct or indirect we can see there is a difference in how they are applied, but not necessarily in what they are applied to. In this section the techniques are looked at in more detail. Of the indirect techniques available, there are image based and range based methods.

3.1 Indirect survey techniques

The term 'image-based survey' is used to describe rectified photography, photogrammetry and orthophotography. The first uses a single image, while photogrammetry and orthophotography require stereo photography. Image-based survey is limited by the line of sight of the camera when the photographs are taken. That is, if the detail cannot be seen in the photograph it cannot be mapped. Furthermore, for photogrammetry and orthophotography the detail must appear in two adjacent photographs. Photogrammetry is usually used to produce line drawings by an operator tracing round the detail, although the photography should always be available to refer back to. Where there are no obvious lines to collect, photogrammetry can be used to map a surface to produce a digital terrain model (DTM).

Fig 8
Image-based methods are good for the capture of texture and colour. This medieval tiled floor detail is recorded, complete with its condition; wear and accretion are clearly visible in this rectified photomosaic prepared for 1:20 reproduction.

3.1.1 Rectified photography

Rectified photography is a relatively quick and simple survey method and is useful in circumstances where the subject is flat and contains a large amount of textural detail (Fig 8). The technique must, however, be used with caution. A standard photograph of, for example, a wall cannot usually be used to scale off accurate dimensions because of errors caused by one or more of the following:

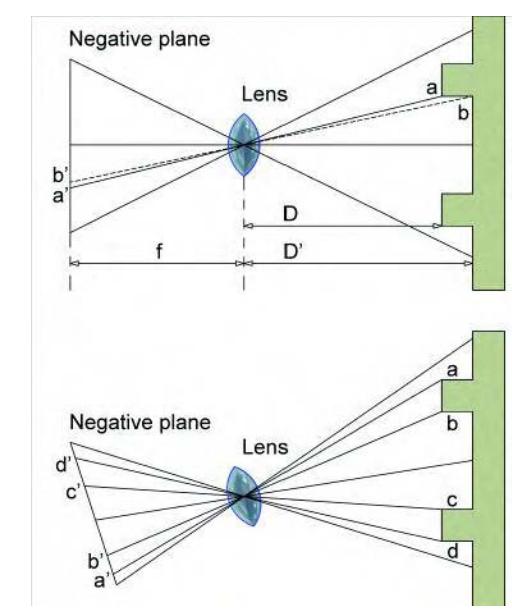


Fig 9
A standard photograph can contain errors of scale as a result of camera tilt and the changing depth of the subject.

1 The camera lens exhibits distortion. This is usually the case with 35mm film cameras and consumer digital cameras, especially those with wide-angle lenses.
2 The facade of the wall is not completely flat, so parts of the wall nearer the camera appear to be larger than those farther away.
3 The photograph was not taken with the image plane of the camera completely parallel to the facade of the wall, so the scale varies across the image (Fig 9).

Fig 10
Rectified photography of a sundial: the severe camera tilt has caused scale variation, which is removed by rectification. Once rectified, the image can be used for scale drawing, provided the tracing is only on the plane of rectification.

To rectify means to correct, adjust or redress an error. In the term ‘rectified photography’ the correction applies to errors in the scale and position of objects in a photograph.

Error reduction:
Although we use the term ‘rectified photography’, the usual aim is to minimise error while taking the photography and to make only minor adjustments by rectification. Error as a result of lens distortion is reduced by using a high-quality medium to large-format camera. Taking care to ensure that the camera is parallel to the facade will lessen the risk of varying scale. Rising front lenses can be used to avoid tilting the camera. If a wall is made up of a number of distinct planes, then it is possible to either scale the same photograph several times or to take separate photographs for each plane. Where a wall is undulating or has highly detailed relief, rectified photography is not suitable.

Scale and control:
To enable the printing of the rectified photograph to a specific scale a method of control must be used. This can take the form of a simple scale bar or targets can be attached to the facade. The distances between the targets can be found with a tape measure or their positions can be co-ordinated using a TST, preferably with reflectorless electromagnetic distance measurement (REDM).

Photographic film negatives can be printed to scale using darkroom methods, but this has been rendered almost obsolete by the widespread adoption of digital cameras. Where darkroom methods are employed the enlarger head has to be raised or lowered until the required scale is achieved by matching the image against a scale rule or a plot of the targets. Slanting the baseboard can compensate for minor tilts. With digital rectification software, four co-ordinated targets per image are usually required, although some systems can make use of assumed horizontals and verticals (Fig 10). A number of stand-alone digital rectification packages are available. Some CAD and GIS packages contain basic rectification routines, or there are more sophisticated plug-ins available at extra cost.

Once the image has been rectified it can either be output directly at the required scale or imported into a CAD package for printing. Here also line work can be digitised or the image can be combined with vector data to produce a composite product. With most digital rectification packages it is possible to mosaic a number of photographs together. This facility is useful for subjects such as tiled floors, where it is impossible to cover the whole subject with one camera shot (Fig 11).

Fig 11
An example of a rectified mosaic: 12 photographs were used in the construction of this mosaic image of a ceiling at Alexandra Palace.

Low-cost rectified photography:
It is possible for rectified photography to be carried out with relatively low-cost equipment and commonly installed software. Small areas can be covered using a standard 35mm film camera or digital single lens reflex (SLR) camera, although the larger the format or number of pixels and the better the quality of the camera, the better the results will be. It should also be remembered that wider angle lenses suffer from greater lens distortion, particularly at the corners of the format. As well as the camera, a tripod, a hot shoe spirit bubble and a 1m long spirit level will be useful.

The camera is mounted on the tripod and levelled using the hot shoe bubble. This ensures that the vertical axis of the image plane is vertical and thus parallel to the facade, assuming the facade is vertical. To set the horizontal axis of the negative plane parallel, the 1m spirit level is positioned level and parallel to the facade. The camera is then rotated from side to side until the spirit level appears to be parallel with the base of the view-finder window or, if a plate camera is being used, the ground-glass back. For this method to work the spirit level must appear close to the bottom or top of the format. Where more than one photograph is required to cover a facade it will usually be necessary to use co-ordinated control targets for scaling rather than just a scale bar. This will help maintain overall accuracy as the distance from the first photograph to the last will be known.

Even without access to specialist rectification software it is still possible to employ rectified photography. Images from digital cameras or scanned negatives can be inserted into drawings in recent CAD packages and rotated to fit detail or control points. Detail can then be digitised on screen or the image can be used as part of the drawing in its own right. Digital images can also be manipulated using photo editing packages to remove distortions due to perspective. It is possible to export an image of control points from a CAD drawing, use it as a layer in the photo-editing package and adjust the distorted image to fit the control. The image can then be imported into the CAD drawing of the control and scaled to fit, thus enabling printing to scale.

To understand the scope and limitations of rectified photography those with little or no previous experience may require field and office practice. The non-professional rectified photographer will also benefit from hands-on knowledge of CAD, access to good-quality 3-D control and a methodical and systematic approach to undertaking survey.

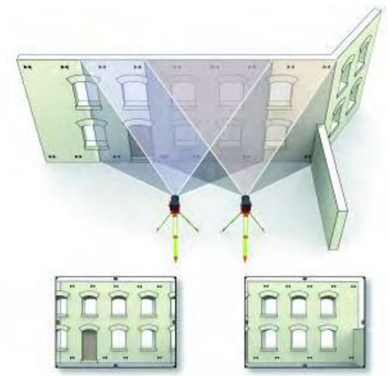


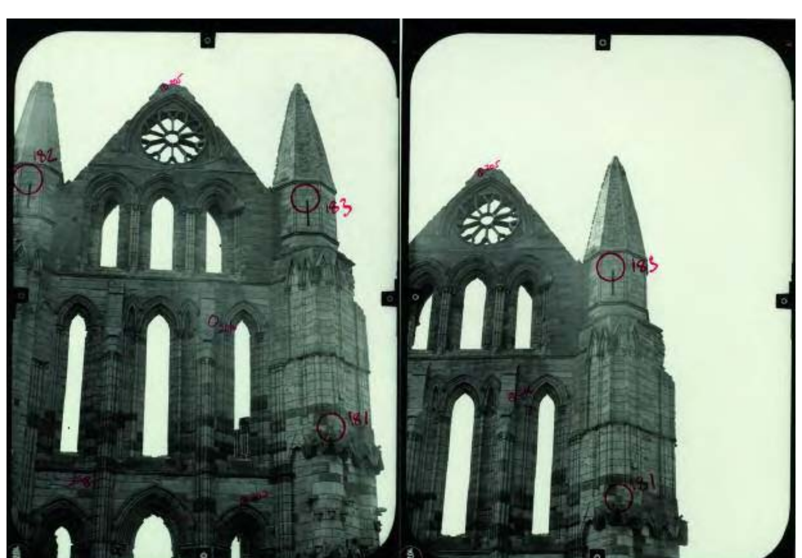
Fig 12
Stereo photographic cover: photographs will ideally have a 60% overlap between them, with at least four control points in the overlap area. In this pair, 3-D capture can be achieved for the middle of the facade, the areas to the left and right of the overlap have no coverage. Stereo pairs are normally taken in strips to ensure adequate coverage.

3.1.2 Photogrammetry

When a line drawing of a large area such as a whole building facade is required, photogrammetry is both the most economical survey method available and also produces the best overall accuracy. It is most effective when applied to subjects where line detail is easily identified, such as an ashlar wall. As the final product is a CAD drawing, it can easily be edited by the end-user.

Photogrammetry is the technique of making precise measurements and drawings from stereo photographs. Stereo photographs are overlapping photographs of the same subject taken from slightly different positions (Figs 12 and 13). The photographs replicate the images captured by each eye. So when the left eye can only see the left image and the right eye can only see the right image, the brain fuses the two images together to form a 3-D image. This can be achieved by various methods, including separate optical trains or special glasses. A standard photograph cannot be used for measurement because inherent within it are the following errors. Firstly, it is a perspective projection, which means that if the subject has any depth or if the camera is tilted relative to the facade there will be scale or displacement errors. Secondly, standard cameras can also exhibit lens and film distortion. The photogrammetric process uses specially made 'metric' cameras that have little or no lens distortion and contain a mechanism for ensuring film flatness. They also have small reference points in the negative plane, known as fiducial marks, which appear in the image and allow for subsequent correction of any film distortion that may occur (Fig 13). The cameras are calibrated so that the focal length and any lens distortion are precisely known. Digital cameras are now frequently used for photogrammetry. They obviously do not suffer from film distortion and therefore do not need fiducial marks, but still require the lens to be calibrated.

Fig 13
Stereo pair of Whitby Abbye: eight stereo pairs were required to provide complete cover of the north face of the North Transept of Whitby Abbey church. The metric camera used for this pair was of 5in × 7in format with a 300mm lens. The red notation on the stereo pair marks the targets and detail points used for control. Note the fiducial marks on the border of the image: here they take the form of small circles, although the type of mark depends on the camera.



In order to eliminate the problems caused by perspective projection, two overlapping photographs, known as a stereo pair, are acquired. The photographs should be taken as square-on to the subject as possible, but if necessary tilts of up to 30° can be accommodated. The farther away the camera is from the subject the greater the area covered in one stereo pair, but to maintain accuracy the image resolution must be within certain constraints, depending on the final survey scale. As a result it is often necessary to acquire a number of stereo pairs to cover one subject, such as a building facade. Each stereo pair will overlap with its neighbours so as to ensure complete coverage.

The stereo pairs are set up using a photogrammetric workstation, which makes it possible for photographs to be viewed as a 3-D stereo model. The workstations are either computer-controlled optical mechanical systems that use transparencies, or most commonly computer systems that use digital images. The stereo model is an orthographic projection, which means that it is not subject to errors caused by the relief of the subject. The two photographs are adjusted with regard to each other to eliminate errors resulting from different tilts of the camera when each photograph was taken.

In order to make precise measurements from the stereo model and to relate it to any other models, control points with 3-D co-ordinate values are required. These usually take the form of small plastic targets attached to the subject before the photography is acquired. Alternatively, existing points of detail may be used. The targets are co-ordinated using intersection or REDM. The co-ordinates will generally be on a site grid so that different facades can be related to one another.

Fig 14
Analytical stereo plotter: the stereo pair is loaded, orientated and viewed before features are extracted by tracing using the hand wheels (x and y axes) and foot wheel (z axis). The linework is stored as CAD data.

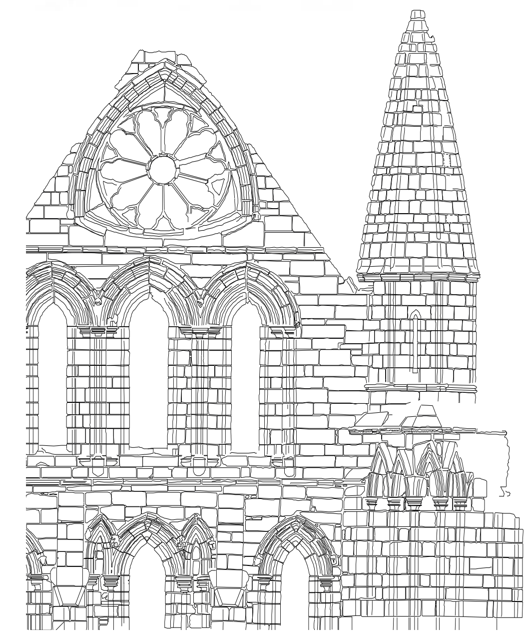


Fig 15
Part of the photogrammetric drawing of the North Transept of Whitby Abbey church, plotted from a CAD file.

Once the stereo model has been set-up it is possible to take measurements or trace off detail using a measuring mark or floating mark, which appears in the 3-D view. A skilled operator using two hand wheels and a foot wheel (one for each of the three dimensions) controls the mark (Fig 14). In order to produce an accurate drawing, the operator must control the floating mark so that it appears to rest on the detail, which is being traced round. Co-ordinates are fed into a CAD system to form the drawing (Fig 15). The content of the drawing will depend on the detail visible in the photographs and the operator's interpretation of the detail. Where, for example, a window reveal is not visible in both photographs it will not be possible to record any detail. Surfaces of elevations or landscapes can be mapped by recording 3-D points on a grid to produce a DTM (Fig 16). With a digital photogrammetric system it is possible to automatically produce a DTM that can then be used either in its own right or to generate an orthophotograph.

Low-cost photogrammetry:
One of the limitations to applying photogrammetry has typically been cost. Coupled with the technical constraints of

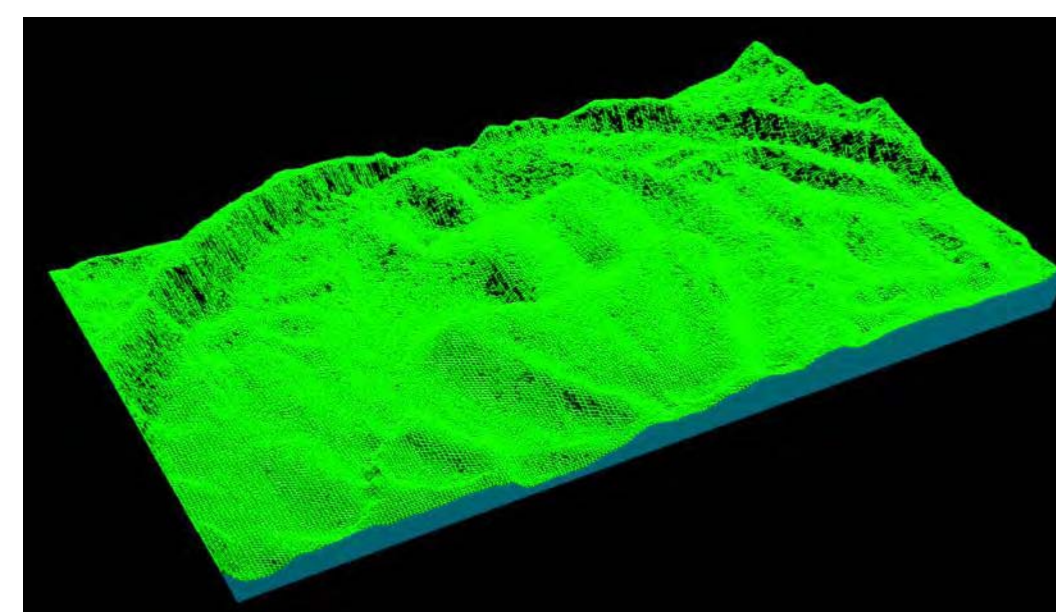


Fig 16
Screen shot of a DTM produced from a stereo pair: this figure forms part of a medieval tympanum that has subsequently been re-used in a folly at Shobdon Arches, Herefordshire.

having to use both specialist cameras and plotting equipment, this has impeded its wide-scale adoption by non-specialist users in the heritage sector.

Digital cameras are now widely available and the previous limitation to their broad adoption within photogrammetry, that of image resolution, is now rapidly disappearing. Sensors in excess of 22 MPixel are increasingly being used in digital SLR cameras from all the major manufacturers. Resolutions of some of the current high-end cameras are even exceeding the equivalent grain-size of traditional photographic film, albeit at a high price. At the other extreme, the image resolution of consumer-grade compact digital cameras now usually exceeds 5 MPixel. Existing research has already found 5 MPixels to be an appropriate entry-point for low-cost photogrammetry (Chandler *et al* 2005, 12–26) such that with suitable care, and working within a 1m range of the subject, sub-mm survey accuracies are possible. However, in order to achieve even near this accuracy, camera calibration is essential. Calibration has traditionally been performed in university laboratories, using multiple imagery of a precisely observed test-wall. This obviously attracts a cost but these days it can also be done by the user with the calibration routines that are now part of most lower-cost photogrammetric software packages.

Although it is possible to extract survey data from just a pair of images, the introduction of a scale will significantly add to its value and utility. Even within a low-cost context, the traditional approach of TST observation to fixed targets – a minimum of four points per stereo pair is required – will improve survey accuracy. In addition, the use of targets will help with more complex projects, for which several stereo pairs are often required to achieve complete coverage. It is not always possible to attach targets to the subject, or a TST may not be available, so if this is the case the use of scale bars placed within each stereo pair, ideally in both the horizontal and vertical axes, will enable the real-world scaling of any processed data. Where neither targets nor scale bars are available, a single measurement on the subject itself will suffice.

The migration of photogrammetric workstations from optical-mechanical machines to PC-based digital systems has significantly reduced hardware costs. Fully featured photogrammetric software, however, still represents a significant investment of at least £30,000. At the opposite end of the price scale, low-cost (less than £1,000) photogrammetric packages have existed for a number of years and principally rely on convergent, multi-overlap imagery rather than on the traditional square-on stereo pair. Although still enabling 3-D survey data to be generated – principally in a point-by-point manner, from digital images – they do not offer the processing tools found in high-end (high-cost) packages. For basic drawings or 3-D model generation this may not be a problem, but intermediate cost solutions (less than £5,000) – which include some or all of the following – have in recent years started to become available to the non-professional surveyor:

- automatic DTM generation
- orthophotograph production
- bundle adjustment software, to accurately link multiple image sets together
- 3-D vector digitising
- stereo display

3.1.3 Orthophotography

An orthophotograph is a photograph that has been corrected for any errors arising out of tilts of the camera relative to the subject or its relief, that is, there is no variation in scale across the image (Figs 17 and 18). Orthophotographs are useful when an image-based product is required but the subject is too 3-D for rectified photography to be applied.

Using the digital photogrammetric process it is possible to produce a DTM that is an accurate representation of the surface of the land or elevation of a building (Fig 16). The DTM can then be used to adjust the scale of an image, pixel by pixel, and thus convert a photograph with perspective projection into one with an orthographic projection – an orthophotograph. The stereo photography for an orthophotograph of a building must be taken as square-on to the facade as possible so as to minimise any gaps in the image that might occur (eg where a cornice obscures the detail above it).

Once the orthphotograph has been produced it can be printed out at the required scale or imported into a CAD package. Within the CAD package it can be combined with line data from conventional photogrammetry to produce a composite product. It should be remembered that an orthophotograph is a 2-D product, and so will contain no Z co-ordinate values and therefore no depth information. It is possible, however, to drape the ortho-photographic image over the DTM using a 3-D modelling or visualisation package.

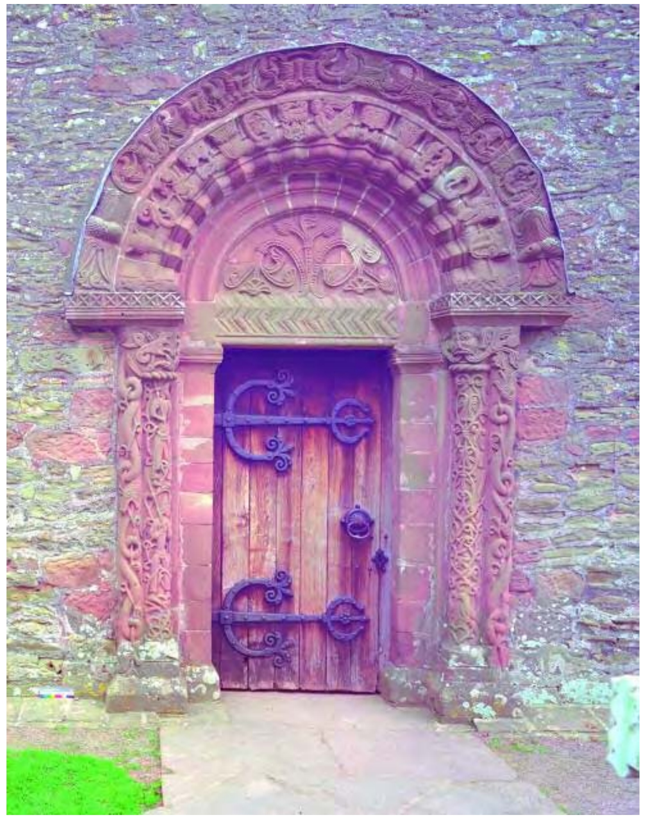


Fig 17
A standard photograph of the South Doorway of Kilpeck church, showing scale distortion.

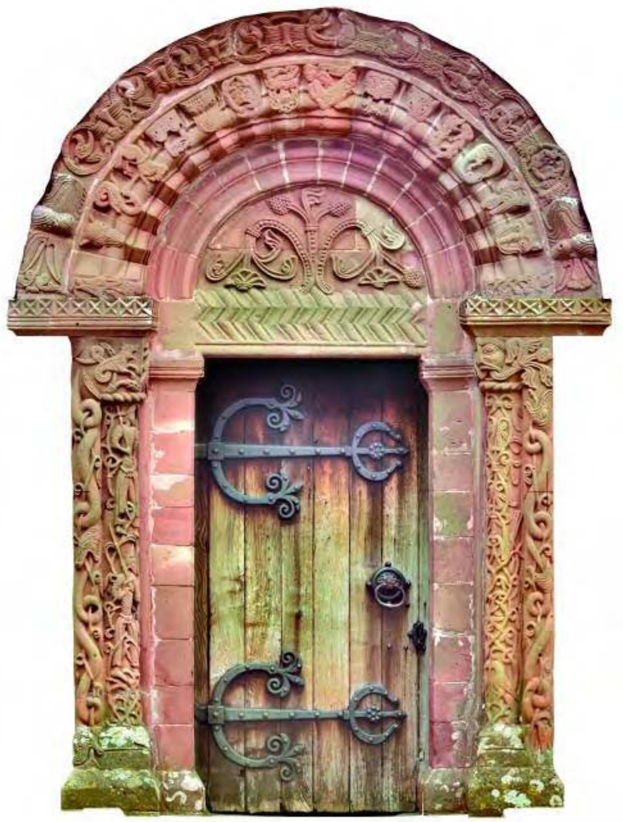


Fig 18
An orthophotograph of the south doorway of Kilpeck church: the orthoprojection makes it possible to view the entire doorway at the same scale. Topographic detail can be combined with orthophotographs if required, with the line drawing appearing on top of the photographic image.

3.1.4 Application of image-based survey techniques

The decision as to whether an image-based or other survey technique is the most appropriate type of survey for a particular subject is influenced by three factors: fitness for purpose, technical considerations and cost.

Fitness for purpose:
The obvious difference between photogrammetric plotting and orthophotography or rectified photography is that the former results in a line drawing while the latter produce images. In many cases a line drawing is preferred because a certain amount of interpretation is performed while the drawing is made. For example, a line drawing of a coursed-rubble facade will often accentuate the building phases, thus aiding archaeological interpretation. In other cases an image-based product will be required because the textural detail of the subject would not be adequately portrayed by a line drawing (eg the colours of different lithologies or the intricate detail of wall paintings).

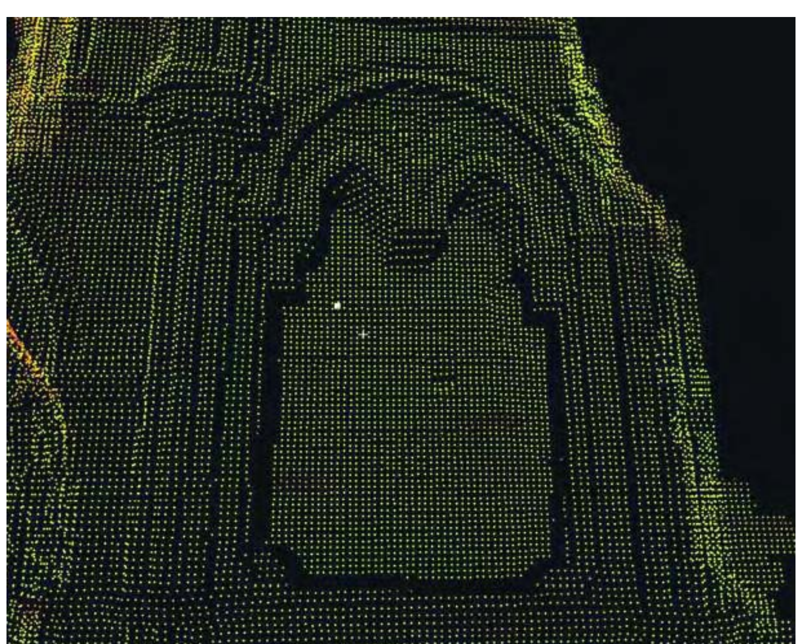
Technical considerations:
The successful application of rectified photography needs careful consideration. It can be used to produce an accurate survey of walls, floors and ceilings, but only if the subject is flat. Where the subject is 3-D because of openings, changes in building phase and fabric loss, or is undulating (eg an historic floor), another method must be employed. The use of stereo pairs enables photogrammetry and orthophotography to be applied to a 3–D subject. The end-product of orthophotography is a 2-D image, unlike the 3-D photogrammetric drawing, so consideration has to be given as to whether the survey will be analysed in three dimensions.

Digital and analytical photogrammetric systems now enable a line drawing to be produced from very heavily tilted photographs. Nevertheless, rectified photography still needs to be taken as near parallel to the subject as possible. Digital rectification software can cope with quite large tilts but at the expense of image quality. This is because, in effect, the area of the subject farthest from the camera will have been photographed at a smaller scale and thus each pixel in the digital image will cover a larger area. Again, orthophotography can cope with the same tilts as conventional photogrammetry, but where detail is hidden from the camera the surrounding pixels will be stretched to fill in the gaps, with messy results.

Cost:
Commercially procured orthophotography is usually twice the price of rectified photography and photogrammetry is three times the cost, so it is important to decide what survey product is really needed. If the survey is required as a pre-intervention or ante-disaster record then a photogrammetry fieldwork package may be all that is necessary. This would result in a considerable cost saving and would also still facilitate the production of drawings at a later date if required. If high degrees of accuracy are not necessary, then rectified photography can be used on a slightly non-planar 3-D subject and the inherent errors accepted as the price for cost saving.

If a cheap but inappropriate survey method is employed, the danger is that any cost savings will be lost owing to the miscalculation of quantities or as a result of extra staff time required to correct the survey.

Fig 19
Point density failure: the 'point cloud' does not have sufficient density to derive detail for drawings at commonly used scales, and feature definition is very poor. The post spacing is 10mm; a post spacing of 1–2mm would be required in areas with complex mouldings in order to define their forms sufficiently.



3.1.5 Laser scanning

A laser scanner is a device for the mass-capture of 3-D data by use of rapid-range measurement, generating hundreds, and in many cases thousands, of discrete points per second in near real time. The resultant mass of 3-D co-ordinate data is known as a 'point cloud' (Fig 19).

Laser scanners used in building measurement are usually positioned on or near the ground (and are therefore referred to as 'terrestrial laser scanners'), but for other applications, such as wide-area topographic survey, the technology can also be airborne, in which case the term LiDAR (Light Detection and Ranging) is often used. Airborne systems use GPS linked to an INS (inertial navigation system) so that the position, path and altitude of the scanner is known as it measures surface information. Depending on the type of scanner, as well as measuring X, Y and Z co-ordinates on the subject, it can also simultaneously measure other values, such as reflectance and colour.

Many industries use laser scan data in a variety of ways, for example the mapping and management of plant and pipework. The heritage sector has a range of applications for which laser scanners can be useful, for example 3-D recording of surfaces not suited to photogrammetric coverage (eg sculptural details, mine shafts, vault webs, dome and pendentive soffits, ship profiles etc), providing data for 3-D modelling or to aid in the production of replicas.

Types of scanner:
In general, laser scanners operate using one of three systems: triangulation, phase comparison and time-of-flight (Fig 20). Each is suited to particular end products.

Triangulation is used for smaller subjects (eg statuary, detached masonry, small finds) that can be positioned close to the scanner. This method can achieve sub-millimetre accuracy and produces very dense point clouds, with post spacing (the distance between points) typically ranging between 0.1mm and 2mm. The scanner shines a laser onto the subject, which is picked up by a camera or charge-coupled device (CCD). Thus the laser emitter, the CCD and the laser dot on the subject form a triangle. With known distances between the CCD and the emitter, the angle of the emitter known, and the angle of the CCD or camera

known from the location of the laser dot in the field of view, by using the principles of triangulation the scanner can therefore calculate the position of a point on the surface of the object.

Time-of-flight and phase-comparison scanners are used for larger subjects, such as building facades or landscape features and are generally operated at distances of at least 2m from the subject. The former produce measurements up to 500m from the subject (with an accuracy of 3–6mm at *c* 100m), while the latter operates up to a range of 50m with an accuracy of 5mm. The time-of-flight systems calculate the distance from scanner to subject based on the time it takes for a pulse of light to travel from the emitter to the subject and back. As the speed of light is known, the distance to the subject can be calculated. The phase-comparison method calculates distance by sending a phased pulse of light and analysing the variation of signal sent and received by the scanner. It generally operates best 'between' the ranges offered by the other methods.

Other systems are also available: structured light scanners, for example, project a light pattern of known geometry onto the subject, and examine the deformation of the pattern as it covers the subject.

Application:
Laser scanning can supply large volumes of measured data rapidly and with predictable precision. It is currently best suited to the capture of surface descriptive information. Laser scanners are effective 3-D surface mappers for a variety of features, including caves, standing stones, quarry faces and tunnels, as well as eroded or irregular features such as weathered mud-brick structures (Fig 21). Subjects like these are often difficult to describe other than as surfaces (principally because of a lack of defined edges).

The technique is, however, unsuitable for subjects where edge definition is important. Vector products that compare favourably with drawings generated by photogrammetry or REDM are not currently easily extracted from laser scans. For example, the edges and mouldings that characterise most architectural subjects can be indistinct in the point cloud and the extraction of such edges from the data set without using supplementary information – such as a photograph, measured drawing or photogrammetric survey – is at present somewhat trying and time consuming.

Fig 20
Laser scanners: top, a triangulation scanner, used for high-density capture of small objects at close range (c $2m^3$ object size at 2m range); middle, a time-of-flight type, used for large objects at long range (50–100m^3 at 3m to 100m range); bottom, a phase comparison type, used for high-speed capture of large objects at long range (50–100m^3 at 3m to 100m range) (image courtesy of Z+F UK).

Fig 21
Triangulation scanner data: small, smooth-surfaced objects make good subjects for triangulation scanners. Laser scanning can support the study of rock art by providing rapid, standardised data sets of scattered objects, aiding the distributed analysis of carved patterns of this kind. Sculptural details can be captured successfully using such scanners, but getting the scanner to the subject on a stable platform can be a challenge.

Increasing point densities in selected areas is possible, but the benefits of speed are lost with the concomitant rise in data volume. Although subjects such as building facades are better dealt with by photogrammetry, if a set of drawings is the required product, laser scanning, especially when used in conjunction with photogrammetric survey, is a useful mapping technique for assessing, for example, gross deformation or weathering of stone surfaces.

Because it is using light to measure, laser scanning is susceptible to variable point-for-point accuracy in a similar fashion to a reflectorless TST: variations in target reflectance, obliqueness and range will affect the accuracy of recorded points to differing degrees within a single scan. They are also analogous to cameras, in that they have a (usually) conic field of view and are unable to measure on surfaces that are not within that field of view (Fig 22). As these are automated systems, the operator is often unable to verify the data sets at anything other than a gross level at the time of capture, although some scanning devices attempt to ameliorate this issue by recording a video or a series of photographs of the subject to aid interpretation of the recorded data.

Expense is another factor to consider. The laser scanner itself is very expensive, and owing to the large amounts of data generated by the scanning process, it is necessary to have computer hardware suitable for handling the demands of processing huge data sets. Software is also integral to the processing of data generated by a scanner and it is necessary to have suitable packages for processing the data from field to finish. Most of the more popular CAD and 3-D modelling packages available do not have the facility to deal with such data 'out of the box'. The integration of processed scan data with traditional vector products for drawing production, often requiring feature extraction and modelling to be of use to the conservation profession, can be a difficult and costly process.

The density of point measurement is intrinsic to the geometric and narrative accuracy of any derived data. An appropriate point density is therefore required. The density of measurement should also be chosen with reference to the accuracy of individual point measurements.

Fig 22
Phase based scanner data with RGB overlay: this image of a 3-D data set shows the coverage possible from a terrestrial scanner. The patches of 'sky' in the facade are areas where there is no data due to interference from obstructions, in this case the cornice and balcony railings. The simultaneous capture of RGB data adds to the richness of the model.

For example, scanning at a density well below the accuracy of the measurement will result in a high level of noise in the resulting point cloud.

As a general rule the point density should be at least half the size of the smallest feature that is required to be discernible in the scan. The smaller the distance between points the more likely it is that the feature will be discernible in the data. This will, however, be at the expense of larger file sizes. In order to minimise the creation of scanning artefacts within the scanning process, point densities should be equal in both scanning axes. Uneven point densities may lead, for example, to the lack of definition of horizontal or vertical features. For most instruments point density during the scanning process depends on the range to an object. It is, therefore, not normally possible to maintain a constant point density over an entire subject during the scanning process. It is most likely, however, that a particular area will be of interest, such as a facade, or building detail and that a regular density of points is preferable. The point density specified by the client or selected by the contractor should be understood as the maximum value for the subject in question.

The great value of a laser scanner is the comparative speed of mass 3-D capture. The processing of surface data from point clouds is very fast and this is a huge benefit in landscape survey from LiDAR data.

Laser scan data cannot record condition of a site in the same way that image-based techniques can, so a co-incident programme of photography is a wise precaution when opting to use laser scanning.

> A simple guide to point density is the ratio between the object size and the point spacing in the point cloud. This is described by the 'Nyquist-Lange' formula:
>
> $$Q = l - (m/l)$$
>
> Where:
>
> Q= quality ratio
> m= post spacing
> l= the smallest object size to be recorded
>
> A positive value of Q of between 0 and 1 indicates a sampling rate that would be expected to be a good match between point spacing and minimum object size.

3.2 Direct survey techniques

Direct survey techniques often add interpretation to or completion of data gathered by indirect techniques (for example, adding missing details and field checking photogrammetry or laser scan surveys). They are also used when there is a requirement for selection at the point of data capture.

3.2.1 Surveying with a TST

Survey with a TST (Fig 23) is rapid and precise but requires the surveyor to select the data to be recorded in the field. Instrument observations are made from fixed points or stations. Depending on the size and complexity of the job, further stations may be set out as required or a traverse used to link sets observations together. Operators of TSTs should be familiar with common survey practice so that they can set up over a point and understand:

- the selection criteria for the points to be measured;
- the performance of angular and distance measurement required to meet the precision requirement of the survey;
- the importance of level and plumb axes for measurement, calibration and verification of instrument error;
- the correct sequence of measurement to ensure appropriate precision for both control and detail work;
- and the appropriate point density for the desired drawing quality at a given scale.

Fig 23
Typical TST, fitted to a tripod: a TST measures angles and distances precisely, one point at a time. This example has both a standard EDM and reflectorless measurement capability.

Because data from a TST is digital, it is easily used in CAD and can be employed to:

- build up CAD drawings directly on site;
- construct wire frame to control (hand) measured survey;
- control the rectification and digitising of drawings and photographs;
- and infill and supplement 3-D photogrammetric, laser scan or GPS data.

Overview:
A TST combines precise distance and angular measurement with a data logging capacity to record 3-D points at ranges from approximately 0.25m to 2000m. Distances are measured by emitting a beam (usually infra-red) and recording the signal reflected from the target. By combining the distance measurement with the horizontal and vertical angles between the instrument and the target, 3-D co-ordinates are calculated. Maximum range can be extended by using special prism arrays. Rapid and precise measurement using a TST gives a reliable framework for survey work of all kinds, but is especially effective in close-range work (0.25 to 100m).

Precision is dependant on the condition of the equipment and on the measurement procedure. Most modern instruments measure angles to between 0.5 seconds and 7 seconds of arc, and distances to between 0.1mm and 10mm (the differences dependant largely on price). The precision of the results is a function of the internal tolerances of the instrument, the range over which it is applied, the operation of correct measurement procedure, the reflective qualities of the target and, to a lesser extent, atmospheric conditions. When the measured angles and distances (including the heights of the instrument and target above the ground) are combined, typical precision of between 3mm and 10mm per point is achieved for single shots and sub-millimetre for rigorously observed control with a high quality instrument.

3.2.1.1 Sources of error

There are three principle kinds of error when using a TST: random, systematic and gross. Random errors (eg transitory obstruction of measurement beam) cannot be avoided, but their presence must be detected by anticipation of a given result. Systematic errors can usually be ameliorated by good procedure. Gross errors are usually the result of a major omission in observation procedure, for example failing to record the correct height of target when measuring points with a detail pole. The commonest systematic errors are described below, as nearly all of these can be compensated for by use of the correct application of procedure or by correct use of the instrument itself.

Additive errors:
The distance measured by the EDM may require adjustment due to the instrument measurement position not being centred relative to the instrument (ie not vertically centred over the point being measured from) and/or by the zero axis of the prism not being vertically aligned over the centre of the tribrach (commonly referred to as the prism constant). These are commonly combined to form the additive error.
The former value is constant for any given instrument, and usually compensated for by the instrument automatically. It is often the latter that can cause some problems, as it is variable from prism type to prism type (typical values are 0, -17.5mm, -34mm), and these are therefore not compensated for automatically by the instrument. If switching between two prisms with different constants (as the centring offset is known), you must remember to change the prism type used on the instrument before taking a shot, or the results will be in error. Similarly, you must remember to switch between reflector and reflectorless modes as appropriate before measurement commences if using REDM.

Scalar errors:
Scalar errors can have a number of causes, but are usually caused by variations in atmospheric temperature and pressure, which cause changes in the velocity of the transmitted beam, and therefore change in the wavelength. The 'thinner' the atmosphere, the longer the wavelength of the beam. These errors are expressed in parts per million (ppm) and can be compensated for when using the TST (usually by inputting the revised data in the appropriate section of the on-board software) if the temperature and atmospheric pressure are measured. As an example, a 1° change in dry bulb temperature is roughly equivalent to a scalar error of about 1ppm, or 1mm per km. Where a site covers a large area or is to be recorded as part of a wider area, project co-ordinate values need to respect the projection used to map the wider area.

Local and national grids use a projection to transfer the curvature of the earth and the effects of variation in height to a plane.

A scale factor is used to correct for the projection used: this can be applied at the point of capture or as a post-process adjustment. It is important to ensure that if a scale factor is to be applied, all members of the recording team are aware of this, so that the mismatch between adjusted and unadjusted work can be anticipated. Control points derived from GPS survey should be supplied with a statement of the projection used and a local scale factor.

3.2.1.2 Reflectorless measurement

TSTs are usually now available with a reflectorless function. This is very useful for building recording work as TSTs will operate over a useful range of 0.5m to 1000m without needing a prism to return the EDM signal. This has two principal benefits:

- speed of targeting;
- and access to remote targets.

Data captured using a Reflectorless EDM needs to be monitored, because the measured distance is affected by several factors:

- range: The return signal is diminished and the contact area of the measuring beam is increased with long-range observations.
- obliqueness: Ambiguity over the point targeted increases with the obliqueness of the observation, and distances can be incorrectly recorded.
- reflectance: The reflective quality and surface texture of the target will affect the ability to measure distances.

Target and station positions for detail work are determined by these variables: stations will need to be close to the subject, and targeting to edges with an oblique aspect to the instrument should be avoided.

Four simple steps will help to get the best from reflectorless measurement:

1. Use a real-time CAD system to monitor the recorded points and lines for verification of the measurement results.
2. Use a card target to define edges; this will improve accuracy when measuring to them, as it will resolve split-beam ambiguities.
3. Keep the range and obliqueness to a minimum.
4. Make some overlapping observations (separated by layer in CAD) from one instrument set up to the next as a check against error.

A reflectorless TST can be operated as a one-person system given the redundancy of placing a prism or other reflector at the target. In practise, two people are often required because subjects usually require a mix of targeting methods to provide complete coverage.

3.2.1.3 Data logging methods

Data logging methods can be divided into two types:

1. Post-process – for which the measured data is stored at capture and developed into a finished drawing at a later date. If rapid capture and field equipment survival are more important than detailed verification, a post-process approach will give the benefit of robust field kit with low power requirements. Many TSTs are now supplied with sufficient on-board memory to record control and detail data directly in the field. If this functionality is not available, a separate data logger can be used. Field codes are attached to observations by the operator as a means of data separation and definition (for example to identify line type, feature type, line start/stop etc). The major shortcoming of the post-process method is that mistakes cannot be easily detected and remedied on site – if errors are detected, the relevant detail must be re-surveyed the following day. This can be problematic in situations where site access is limited.
2. Real-time CAD – a method of digitising 3-D data from the instrument directly into CAD. The use of real-time CAD capture is of great benefit for large-scale, close-range work, such as the recording of detail for historic building surveys. The surveyor can capture detail using the TST to position points and lines in the 3-D CAD drawing, and can view the data as it develops, avoiding potentially costly omissions and mistakes.

Ruggedised computers vary widely in specification and performance. It is important to check carefully details like power supply and screen performance before choosing a field unit. It should be able to run an industry-standard CAD

Fig 24
Real-time CAD set-up in use: the tablet PC makes it possible to see and check the CAD work as the data are captured, a useful method for detail work using a TST.

application in the field. For real-time CAD work, the best field computers are those that use a pen interface and have daylight-readable screens (Fig 24). These are more costly than a standard laptop or PDA and may need an external power supply or spare batteries. Weather protection is important and all connections will need to be robust.

3.2.1.4 Typical applications for TST survey

The TST is extremely flexible and has a wide range of survey applications, including the generation of precise control data, topographic and building surveys and, subject to the correct control regime, for monitoring structural and other physical movement. Until the advent of affordable survey grade GPS it was the principle tool for undertaking topographic survey, a task to which it is still well suited, although limited to some extent by the requirement for a line of sight to a target to work.

DTM generation from TST data is effective and the height precision achieved is good, although indirect techniques (such as aerial photogrammetry or LiDAR) can map landscape surfaces over wide areas very rapidly: if the landscape requires interpretation (such as the identification of man-made features, break-lines etc) a direct technique like TST or GPS survey has the advantage of placing the data selection process in the hands of the surveyor at the point of capture.

In building survey, a TST (particularly when used in reflectorless mode) is an invaluable tool for the production of plans, sections and elevations (Fig 25), for deriving site-wide control by traverse and for providing control for rectified photography. When using a direct technique like TST survey, confidence in data selection is important: it will be only the selected information that is transmitted, and therefore verifying the selection of points and their correct presentation is crucial. The guidance offered is based on practical experience: the outcomes from survey have a theoretical basis, but it should be remembered that survey is a practical art and has long been recognised as such.

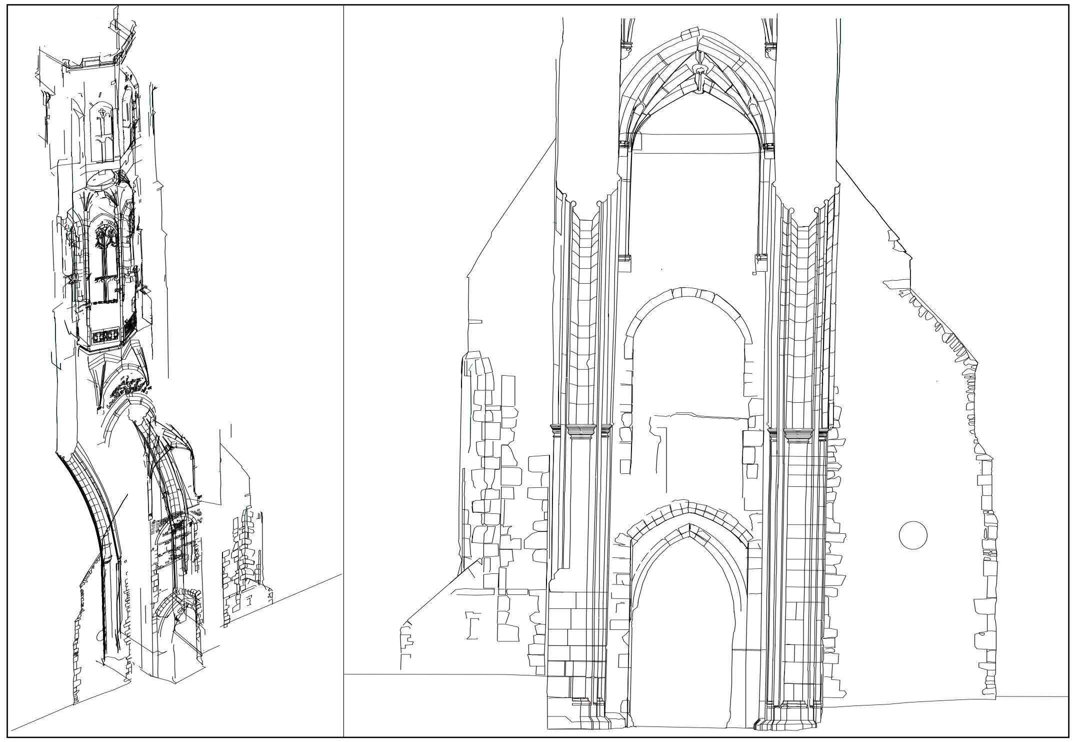


Fig 25
A sectional elevation prepared for fieldwork: viewports in CAD enable the data to be viewed from different angles. This facility makes it possible to identify and understand the 3-D building data being recorded, which means that informed decisions can be made about any further data capture required on site.

3.2.2 Site drawing

There are three types of drawing used in heritage documentation: direct plotted drawings, measured drawings and sketch diagrams. Each has its role according to the information requirements of the project in hand. Each method has its strengths and weaknesses. Direct plots are very time-consuming but are the most reliable in terms of scale; measured drawings are fast on site but selective in nature, and it is often difficult to resolve missing measurements at plot time; sketch diagrams can be very important in conveying understanding (especially of building construction detail) but without supporting measurements they are of limited metric value.

A photograph will support a drawing and vice-versa. Use the camera to photograph what cannot be drawn and draw what you cannot photograph. Photography can be used as an *aide-memoir* and should reinforce the observation used for drawing. Drawing, like all recording methods, works best in conjunction with other techniques, such as photography, which complements drawing well by recording colour, texture and undifferentiated form.

3.2.2.1 Directly plotted drawings

Drawings made by plotting to scale on site are also known as direct plots, and are usually used as a primary record. The site plot is then traced into CAD or 'worked up' as a fair copy for archive record. Generating the scaled plot on site, although time-consuming, produces the most metrically reliable results, provided the control used ensures the precise fit of each individual section to the overall drawing. Direct plots are typically used for 1:20 and 1:10 scale drawings of building elevations, trench profiles in archaeological investigations and also for the plotting of underwater archaeological remains. As a method it is robust and has the virtue of being self-checking: as the drawing progresses the plot can be tested for its fit to the subject.

A string grid is placed over the subject and measurements are transferred to graph paper. A scale rule is useful to convert measurements and with practice many practitioners will end up producing the drawing to scale by eye. Detail can be drawn at scale from calliper or taped measurements. If drawn at 1:1, fitted profiles taken from a profile gauge at full size can be used. Each measurement and profile is added to the plot to build up a scale drawing of the subject. The view of the object selected must match the elevation view chosen for the section and any profiles must be taken accordingly. The fair copy is then traced or digitised directly from the field drawing.

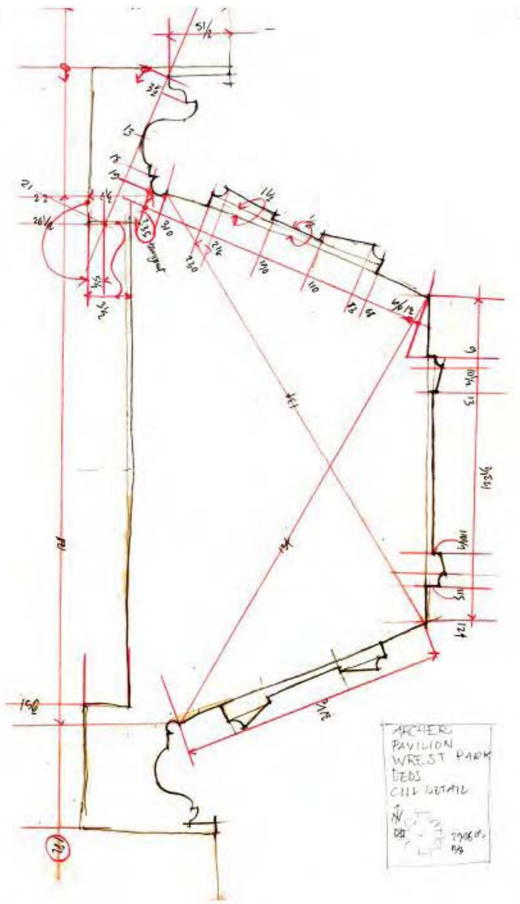
Fig 26
Recording a wall using a rigid recording frame.

Direct plotting is widely used for large-scale work and is the standard method of archaeological excavation drawing. The advantage of direct plotting over dimensioned sketches is that it is possible to tell by looking at the drawing if all the measurements have been recorded. If a critical measurement is missing, the relevant bit of the drawing will be missing. The drawback is that more site time is required to produce a directly plotted drawing.

In the recording of archaeological excavations, a planning frame is used to assist plotting the features revealed by excavation at scale. The drawings may form the record of the context as it is removed, so they need to be based on a reliable and systematic procedure, as there will be no second chance to plot the information. Planning frames need to be level to the reference plane and linked to a common site co-ordinate system to enable the plots from each frame to fit together.

In the case of elevations the frame can be flipped to record the vertical detail (Fig 26). The subject is controlled by the string grid on the planning frame and a fixed tape. The drawing is progressed by marking out the lines at scale referenced to the grid on the plot.

Fig 27
Diagnostic diagram of detail: the moulding is drawn up and measured as an indicative detail to assist in dating a building phase by joinery type.



3.2.2.2 Measured drawings

Sometimes known as dimensioned sketches, measured drawings are a common method of conducting architectural surveys. The method relies on a good clear sketch of the subject being annotated with the dimensions used to replicate the geometry at scale (Fig 27). This is a technique that is fraught with risk, as it is easy to miss measurements. Measured drawing practitioners usually have a strong type-specific knowledge: if there is a failure of understanding, the drawing will be deficient and a return to site will be needed. The great strengths of the technique are the speed of capture and the expression of the draughtsperson's expertise.

The drawing is prepared before measurement. This is skilled work, as it requires the accurate depiction and careful selection of relevant detail. The drawing first and measurement second approach is suited to maximising the surveyor's knowledge of the structure being recorded. Dimensions are added to the sketch in a number of ways. A vertical or horizontal datum for elevations or triangulation for plans achieves control (Fig 28). Control lines are shown on the drawing with a straight or tie line. Measurements to detail are taken at known points along the horizontal or vertical datum and recorded as dimensions on the sketch. It is common practice to plot measurement lines in red and datum or reference lines in blue to separate them from drawn lines. The same line weight emphasis as will appear in the finished plot is used to indicate edges and section lines. Missing measurements can compromise the integrity of the final drawing and are a drawback of this method, especially if the site cannot be revisited. The use of photographs can help to overcome this problem.

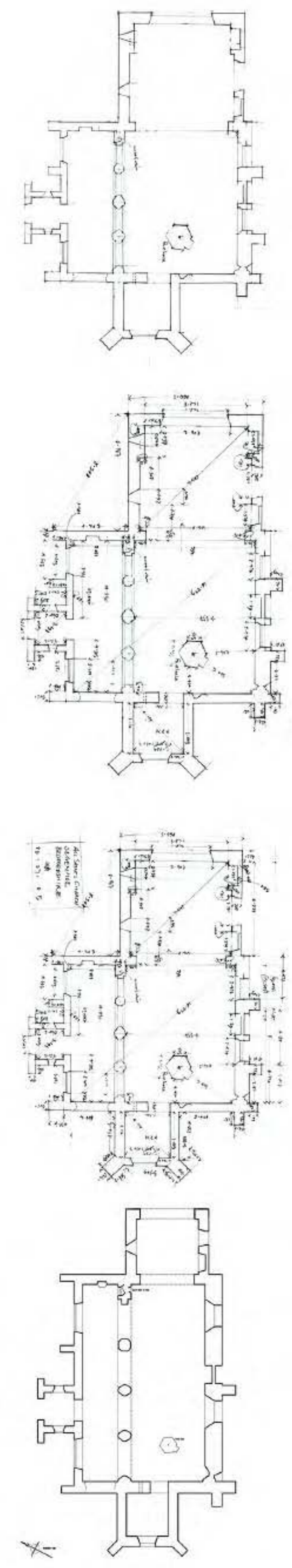


Fig 28
Making a plan from a dimensioned sketch, from site note to plot: the roughly proportioned sketch is prepared by walking the plan both inside and out. Measurements are applied to the sketch systematically working clockwise around the inside and then anticlockwise around the outside. Brace measurements are added. The plot is then worked up in CAD.

3.2.2.3 Sketch diagrams

A sketch diagram is a drawing that explains details of the subject (Fig 29). The sketch shows the key relationships between components, the match or otherwise of prototypes and the explanation of features not apparent from photography.

Sketches are useful when combined with measured data from other sources. It should be remembered that, like all survey techniques, sketching will benefit from a consistent and systematic approach.

Sketches of diagnostic details (features that support a theory about how a structure or component fits in to our understanding of an historical sequence) are valuable records. Once recognised, these key features need to be recorded to substantiate our findings. Site sketches are often an ideal way of doing this.

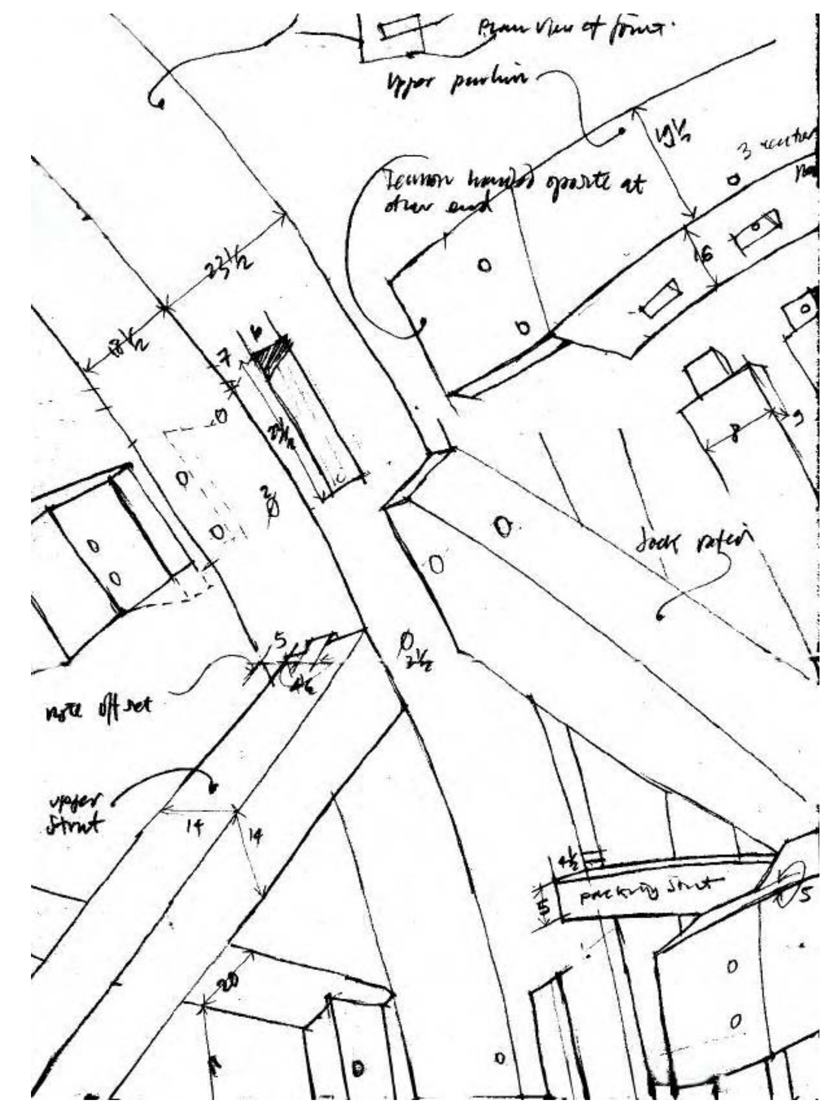
3.2.2.4 Producing measured drawings

When to draw:
Drawing should be used wherever there is a need to record information that is not captured by other techniques. Preparing a drawing takes time and concentration, so selecting what to draw needs both care and a clear understanding of how the drawing will contribute to the aims of the project. While measured drawing can be used as a stand-alone survey technique, it is most effective as a method for completing data from other sources. It is most commonly employed in areas where:

- photogrammetric plots are incomplete;
- infill to CAD wire-frames is required;
- edges in point clouds need definition;
- 3-D modelling requires delineation of edges and hidden detail;
- a thematic layer is to be added to base data;
- access for survey instruments is limited;
- lighting is poor for photography or the definition in a photo will not reveal the required profile or detail;
- or there is a requirement to apply type-specific knowledge to record architectural detail.

Getting measured drawing done:
Making a good drawing for site measurement can be difficult, but the exercise is rewarding. The production of clear and accurate drawings engages the surveyor in careful observation of the building and its details. In selecting the details to be drawn and selecting the lines to record them, the surveyor will be testing the fit of patterns and seeking the forms that define the architecture.

Fig 29
Sketch of timber jointing prepared to augment REDM wire frame for constructing a 3-D model: the sketch shows clearly how the parts fit together, something not always shown on a photo.



The drawing should be executed on a good quality material and with an appropriate weight of pencil lead. Anticipation of corrections and making the drawing 'work' in terms of layout and annotation are important.

There are two main manual methods of measuring: baseline and offset, and braced quadrilateral (also known as taped triangulation).

Baseline and offset:
The base line and its offsets can be shown on the drawing or tabulated elsewhere; the drawing must show the start and end of the baseline and where the offsets are booked.

Braced quadrilateral:
This method involves measuring the diagonals of a room and the wall lengths that close triangles. It is a technique that needs clear and systematic annotation on the drawing.

- Use a drawing board, T-square, rolling ruler or graph paper to ensure that the lines in your drawing are squared up when needed.
- Size the sketch *before you begin*, so that you can fit the whole drawing on the paper and depict the smallest detail at a legible size.

Fig 30
Use of line weight: the value of carefully collected measured information is wasted if it is not transmitted with clarity. The heavier line weight shows features cut by the section, and makes this drawing a spatial record. The cut lines are shown alone above.

- Draw a centre line and place guide lines to get the proportions right. Draw the principle lines with light lines.
- Mark off each of the length measurements – those that you took in the field – on a dimension line. Use a triangle to draw properly spaced, faint guidelines for the elements along the length of the item.
- Working anticlockwise around the plan, draw dimension lines alongside the elements as you measure. Mark off each of the measurements that you take. Use a triangle to draw faint guidelines for each of the measurements. Make sure measurements are controlled, either by triangulation (eg diagonals of rooms) or by reference to a datum or baseline.
- Draw the outline of the item itself using the guidelines that you have just set up. Use a harder lead or a different colour for measurements, and a softer, darker lead to draw the item itself.
- Make space to write the dimensions on the drawing before actually writing them – they are the hardest parts of the drawing to fit in legibly and the most necessary to be read clearly at plot time.

Drawing is an effective way of filling the detail gaps common in metric data sets: it is an effective verification tool. A TST wire frame is a useful tool for positioning drawings, but complete reliance on such data for edge definition is best avoided. It is better to work with what is seen on site for large-scale clarity. The proportions of the drawing need not be metrically precise but it is a key function of the drawing that the selection of edges be clear.

Finding the edges:
In formal survey drawing if something is not defined by an edge it cannot be drawn, so using sketched guide lines will help 'place the edges' and draw them in. Edges are not always clearly defined and some thought will be needed to decide where to place the line. For example a rounded column will have an edge that is dependant entirely on the viewpoint of the observer: for survey drawing this will require the observer to record the line as it will appear on the plane of projection for the elevation.

Using line weights:
The convention for line weight is simple. In a sectional elevation, details on walls use the thinnest line, the outline of openings a thicker line, while the cut-line is the thickest (Fig 30). So the outline of a door opening is shown with a thicker line than the jamb mouldings around it. This is easy to express in the field drawing by using a heavier line on the sketch as appropriate.

Choosing lines:
If there is uncertainty about how a feature should be depicted, then a process of identification, type history and form analysis should be used. If the right questions are asked of the subject, then the drawing will be effective:

- How do the lines bound the subject?
- How is it developed from its design?
- What is the prototype it is derived from?
- What is the architectural form used?
- What are the functions of the component?
- Does the viewpoint affect delineation of edges?

Drawings must show a clear line selection, as the lines clarify the measurement and define the edges selected. Hence drawings are often needed where a photograph could not define the edges needed for a survey.

Anticipate end use:
Because drawing is so dependent on clarity of selection it is important for the draughtsperson to know what the requirements of the survey are:

- Will the drawing clarify the detail to help build a 3-D model?
- Will it enable a wire frame to be edited into a CAD drawing, or will it simply help define edges where they are indistinct?

Annotation:
Descriptive text on the drawing should be limited to describing what is not revealed by the drawing or associated photography. Notes on material, colour and context should be placed well clear of the drawn lines and limited to the requirements of the brief: if the brief calls for a written description you should not be drawing. All drawings, be they measured drawings or sketches, should be clearly and concisely labelled, and the drawing layout should include:

- the site name and location;
- the date of drawing;
- the direction of view;
- the draughtsperson's name;
- and a location diagram.

Metadata:
Metadata is crucial to the utility of the information we record by systematically including the details of who made the drawing and why; the expectations of those using it can then be based on fact rather than on supposition. The title box should contain all the information needed to identify the origin of the drawing and its purpose. It is the declaration of the provenance of the work. Annotations should be used to link ideas to the drawing: for example, a sketch plan can be used as an index to explanatory notes. Where drawings are prepared to supplement other survey data (eg for infilling details in a REDM wire frame) this should be made clear as a note on the drawing.

The site drawings should be prepared in conjunction with the wire frame, if possible, as this is the best way to be aware of the missing faces in the wire frame. If it is not possible to prepare the drawing on site at the time of capture (ie if the wire frame has been prepared by photogrammetry), then careful inspection of the wire frame should be made and a site visit planned to infill the key details by measured drawing.

Integration with CAD:
For 2-D work there are two routes, depending on the type of drawing used. For measured drawing the measurements are plotted directly into CAD as polar or Cartesian co-ordinates. Plotting from drawn notes can be achieved by using offset, circle, arc and line for translating measurements. Direct plots can be digitised by tracing on a digitising tablet or from a scan of the drawing scaled to the wire frame on screen.

The wire frame enables the positioning of prototype profiles, which can be extruded to form the solid geometry bounded by the lines. The wire frame will need supplementary information from site notes to complete the profiles needed. For 3-D work we need measurement of all six faces of a cube rather than the three or so available from any one viewpoint.

When tracing into CAD it is important to anticipate the output scale of the tracing: the CAD view is often misleading when compared to an A1 draughting sheet: a common mistake is to pick fewer points than the scale requires, which will result in 'spiky' lines at plot scale.

Communication of the measured work: Plotting the measured drawing is the final step in sharing the information gathered by drawing. It is at this point in the process that the standards and conventions required must be applied. Standards will describe the correct line weights to use, the required layer structure (for CAD), the correct use of symbols and the correct sheet layout and rubric. Some standards also prescribe the media to be used and the deposit and accession procedures required.

Formal presentation will require a sheet border, title, location plan and scale bar. The extent of the subject, the text styles and sizes should be in agreement with the specification. For large projects or wide-area programmes it is advantageous to plot drawings in CAD for digital transmission. Measured drawings are plotted at scale on archivally approved media in anticipation of the drawing forming a record with a long life. The information on the drawing should be formally organised with the correct convention for line weights, section lines, location diagram etc. Depending on the project requirement, the drawing sheet(s) will contain the drawing elements plan, section and elevation.

When preparing plots in CAD it should be borne in mind that what you see on screen may look very different when plotted. The plotted result should match the drawing requirement: it is wise to test line weights, line type and line style at the plot size before committing a CAD drawing to archive. As the digital drawing has an uncertain future, it is wise to deposit hard copy plotted on archival media together with the CAD drawing issue.

4 Procurement

The procurement of all types of survey can be a useful tool for a number of reasons. It is often the most efficient way to access the skills, resources and equipment necessary for a project. Photogrammetric survey, for example, traditionally requires expensive equipment and highly skilled specialist staff. It would not be economic for an architectural practise or archaeological unit to make the investment needed to be able to undertake photogrammetric surveys on a relatively infrequent basis. Indeed most general surveying companies do not have photogrammetric capabilities and will sub-contract such work. Even when, as is often the case, an archaeological unit has in-house surveyors, they may not have the capacity for every project, and so may need to procure work from external sources.

The precise 3-D recording of historic buildings is a particular application of metric survey that differs from general practice. The required scale for drawings of historic buildings is often greater by a factor of ten than even the most detailed topographic surveys, and most metric surveyors are unfamiliar with the drawing conventions used. When commissioning a survey of an historic building it is therefore advisable to describe the required services with care and, once the survey is in hand, to monitor the process carefully.

Procurement of metric survey for historic buildings can be further complicated by the fact that there are a number of different methods available, as described in previous chapters. Each particular site will require the use of one or more of these methods, and it will be necessary to decide which to use before approaching a suitable contractor. Evidence that the contractor is experienced in the proposed method or methods and their application to historic buildings should be sought.

Even when suitable methods and contractors have been identified a standard specification and a project specific brief will be required in order to guide the survey towards a successful conclusion. It is essential that the brief covers the requirements of the end users but is also realistic as to what can be produced with the resources available. To this end it is advisable to initiate meetings or dialogues with all interested parties so that the scope of the project is fully understood by those procuring the survey, those undertaking the work and those who will be using the final products. It is also worth making a search of the relevant archives in case suitable survey already exists or there is material available that will facilitate the procurement process. For example, old plans of unknown provenance may still be useful at the project planning stage.

4.1 Survey specification

Specifications can either be method-based or performance-based. With the former, the outcome is controlled through the assumption that a particular method will produce a particular result. The later carefully describes the required result, while leaving it up to the contractor to decide how to achieve the result. Performance-based specifications are seen as fairer because they allow a greater variety of contractors to compete for a contract. In practice many specifications contain elements of both types.

Specifications will generally address the following issues:

- the need for a method and resource statement describing the proposed technique and its likely performance, as well as the equipment and its condition (calibration, certification etc), and the procedures, skills and personnel to be applied;
- health and safety procedures;
- professional indemnity requirements;
- the required tolerances for the job in terms of scale and repeatability;
- the control system to be used (the difficulty of using existing site control is often overlooked; it is worth considering the use of GPS to determine OSNG values);
- the possible requirement for Scheduled Monument Consent for the insertion of station markers;

- the required survey products (the specification of the CAD protocols, plot size, line weights etc needs to be undertaken with care, particularly where presentation drawings are important or if the data are to be manipulated by others);
- the archive quality of the output;
- and the number of copies and where the final product is to be sent.

The publication *Metric Survey Specifications for English Heritage* has been used to procure metric surveys by a number of organisations. To date, it has proved a valuable and robust control for the provision of base mapping data in conservation and recording projects. Standard specifications should always be used with care, however, and survey products should never be selected without careful consideration.

A revised and updated edition called *Metric Survey Specifications for Cultural Heritage* is now available at a cost of £40 from the following address, and will also be accessible on the English Heritage website (www.english-heritage.org.uk) as a low-resolution .pdf file:

English Heritage Postal Sales
Gillards
Trident Works
Temple Cloud
Bristol BS39 5AZ
Tel: 01761 452966
(Product Code 51481)

A number of other specifications are available, a selection of which is listed below.

Surveys of Buildings and Utility Services at Scales of 1:500 and Larger. RICS, March 1996; £75

This document principally covers topographic survey at scales of 1:500 to 1:100, rather than detailed architectural surveys.

Vertical Aerial Photography and Derived Digital Imagery. RICS, July 2001; £30

This publication covers all items relevant to an aerial photography survey, such as camera equipment, flying and photo coverage, film products, digital imagery, documentation, storage and preservation.

Understanding Historic Buildings: a guide to good recording practice. English Heritage, 2006; Product Code 51125; free from English Heritage Customer Services.

This guideline is an expansion of the former RCHME publication *Recording Historic Buildings: a descriptive specification*, used to define form and levels of recording.

4.2 The project brief

A standard specification will not cover all eventualities and certainly will not address site-specific issues such as access arrangements. To successfully manage a project the specification will have to be supplemented by a project brief. The client should clearly set out the objectives of the project in the brief for the contractor. Although the responsibility for devising the brief resides with the client, it will benefit from the advice of both survey specialists and historic building analysts. An effective brief will:

- define the purpose of the recording project;
- describe how the survey output will be used;
- outline the proposed survey techniques, elevation by elevation if necessary;

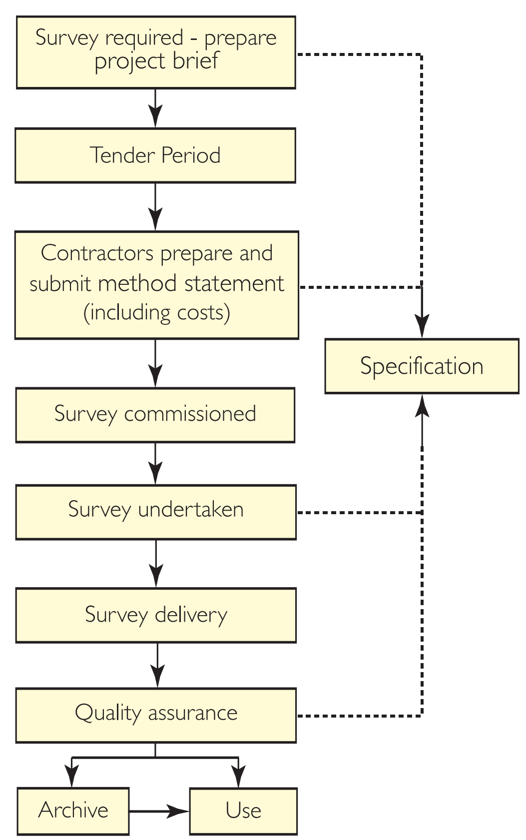


Fig 31
Flow chart of the procurement process: the preparation of the brief should include an assessment of the end-user requirement.

- define the programme of works and the timing of survey activities within the programme, including access, site preparation and scaffolding requirements;
- describe the extent, scale and intensity of the survey, and include a clear relevant example of the treatment of detail (variation of detail cover proportional to scale should be shown by example if necessary);
- and note the practicalities of power, light, access and personnel contacts.

Once the brief has been prepared it can be issued along with the specification to one or more specialist survey contractors for costing. When a price has been agreed and a contractor appointed the contracted personnel should refer to the brief and specification as the work is undertaken. The client can then check the work again with reference to the specification (Fig 31).

4.3 Metric survey project brief

The following is a general checklist of the factors that may need to be considered, although these will vary according to the nature of a particular project. Other site-specific variables will also need to be included in an individual brief as appropriate.

- Site-related information: location, access, site visits, health and safety factors, clearance of vegetation.
- Required liaison with other appointed contractors (eg archaeologists).
- Standard specification for the survey type(s).
- Required accuracy and height data for survey control.
- Required orientation of the survey grid.
- Temporary targets and their removal.
- Use of artificial illumination.
- Use of minor control generated by hand measured survey.
- Completeness.
- Variation in level of detail recorded and/or additional measurement required.
- Variation in the rate and/or mode of recording photogrammetric data.
- Any required phasing of delivery.
- Use of monochrome and/or colour imagery.
- Specific digital format for presentation and storage medium.
- Variation on standard CAD layering or file-naming conventions.
- The required scale of hard-copy output.
- Areas to be provided as initial samples.
- Presentation of circular features (eg the un-peeling of circular towers and their presentation as a flat surface).
- Specific information required on each photograph (eg photographic labels).
- Number and detail of data sets provided and delivery details.
- The precise format and file type of the archive to be held by contractors.

The procurement of survey can be the best way to access resources economically. It can also be fairly straightforward to manage if a number of key points are borne in mind.

Time spent on reconnaissance is seldom wasted. Familiarity with the site and the specific area to be surveyed will help the client foresee any problems and better enable them to respond to queries from the contractor (Fig 32). A good knowledge of the various types of metric survey available and their characteristics will enable the selection of the most appropriate technique or techniques for a particular project.

Rigorous use of a specification and brief as described above should leave no room for doubt about the outcome of the project. But maintaining a dialogue with the contractor throughout the project will also go a long way to achieving the desired outcome.

Once a preliminary survey has been delivered, it should be checked thoroughly, preferably on site, prior to authorisation of final issue and payment.

Fig 32
Without reconnaissance this facade might have been surveyed using an inappropriate technique due to a lack of provision for either infill survey behind the tree or clearance of the facade. A reconnaissance visit will repay the time spent many times over in cases like this.

5
Case studies

5.1 Battle Abbey courthouse: an archaeological survey

The Central Archaeology Service (CAS) of English Heritage (now the Archaeological Projects Team) became involved in a series of projects at Battle Abbey, starting with excavations in 1990. These investigations centred on the gatehouse structure (Fig 33), which is made up of three buildings: the 14th-century gatehouse in the centre, the 16th-century courthouse on the left, as viewed from the town, and the earlier Norman gatehouse on the right (Hare 1985, 13 and CfA archives). When it was decided to convert the courthouse into the main visitor entrance to the site, the CAS was asked to record the historic fabric and conduct excavations in order to aid the design of the new works and to help in the interpretation of the historic building.

Opposite top
Fig 33
Battle Abbey courthouse, viewed from the High Street.

Opposite bottom
Fig 34
The interior of the Battle Abbey courthouse, showing vegetation at wall-head level and the shell of the squash court.

5.1.1 Site survey

The proposals for the shell of the building entailed consolidation and repair of the standing fabric, as well as building a new roof and floor-bearing structure inside, which was to be independent of the historic walls. A detailed drawn record was needed both to serve the architects and to aid archaeological interpretation of the building. To this end, in 1992 a photogrammetric survey was undertaken by the English Heritage Photogrammetric Unit as the most economical way to produce a basic record of the standing walls.

As Figure 34 shows, the primary measured survey in this case took place under less than ideal conditions, since there were patches of vegetation on the masonry and areas of bricked-up detail in the windows. As the primary measured survey was required before any remedial work to clear these obstructions could be implemented, it was left to the hand-survey component of the project to record the missing detail.

The elevation drawings were enhanced by hand-survey techniques to provide an accurate stone-by-stone record of each wall. This elevation record was augmented as excavations in and adjacent to the shell revealed the footings of the walls and other now-vanished structures. As the photogrammetric plotting generated digital data in three dimensions and was supplied in a CAD format, manageable portions of the elevations could be plotted on to paper for use out on site. The entire structure was encased in scaffolding to allow access (Fig 35), and a team of six archaeologists spent six weeks comparing each plotted elevation to the fabric of the building and drawing overlays of corrections and additional information that would aid interpretation.

Left
Fig 35
Scaffolding on the Battle Abbey gatehouse, from which a detailed archaeological investigation and recording of the structure were carried out.

5.1.2 CAD

The CAD elevations had a 1m grid superimposed on them to aid alignment of the individual correction sheets. Each elevation was then plotted at a scale of 1:20 as a series of 5m × 5m tiles on A3 sheets of archive-quality paper. These were taped to plywood boards, overlain with drafting film and taken up on to the scaffolding for direct comparison to the fabric of the walls. Any differences between the plots and the real fabric were marked, as were material types, weathering and other features, such as grooves, cracks and nails (Fig 36).

To take advantage of the 3-D nature of the primary photogrammetric data the corrections were digitised into the supplied CAD drawings at appropriate 3-D co-ordinates to match the surrounding masonry. Within each drawing, as supplied, there was a co-ordinate system that used horizontal distance across the drawing as the x-axis, vertical distance as the y-axis and distance away from an arbitrary plane behind the drawing as the z-axis. As these axes were used when superimposing the 1m grid for the paper plots, these 'elevation' co-ordinate systems, in effect, provided the control for the hand survey. The z-axis defined the surface texture of the wall and represented the one axis not recorded by the hand-drawn corrections.

Figure 37 is an isometric view of data, digitised in the traditional 2-D manner, while Figure 38 shows corrected 3-D data assembled to form a wire frame model of the building for analytical and presentational purposes. The x- and y-axes were generated from the digitising tablet, but the z-axis needed to be derived from the existing CAD files. To achieve the desired effect, detail points near the corrections were interrogated to find the missing axis values to the nearest millimetre and the new points were digitised at the appropriate z-value to match. This provided both corrected 2-D elevation plots and relatively accurate 3-D data for the modelling of the structure at a later date.

In Figure 39 one of the internal elevations is shown with the uncorrected data on the left,

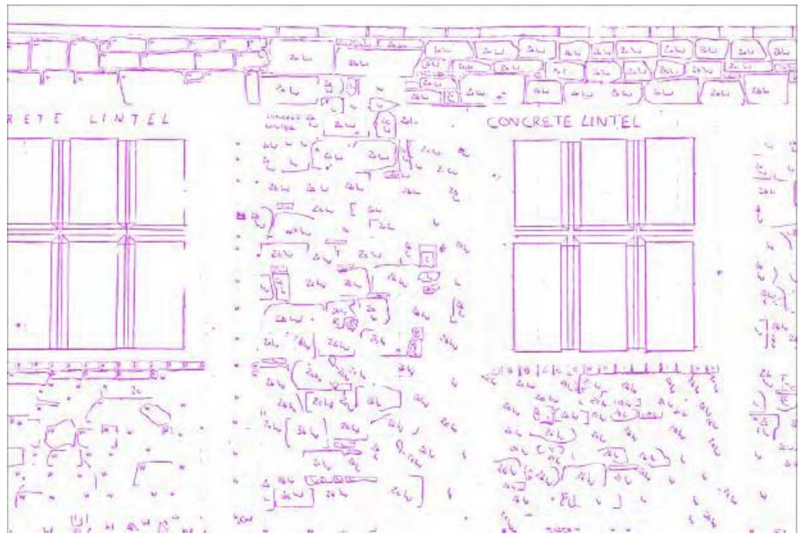
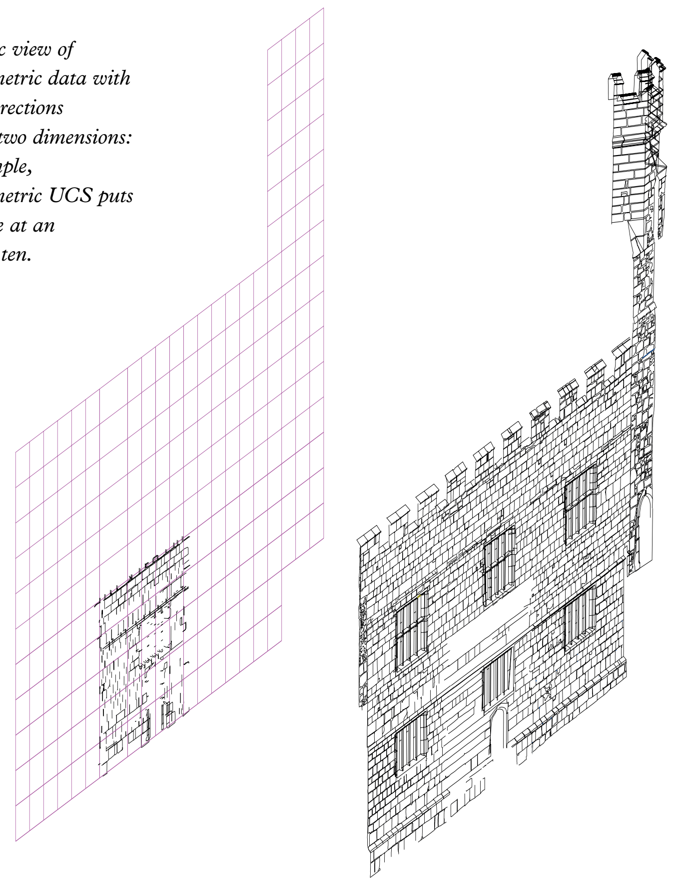


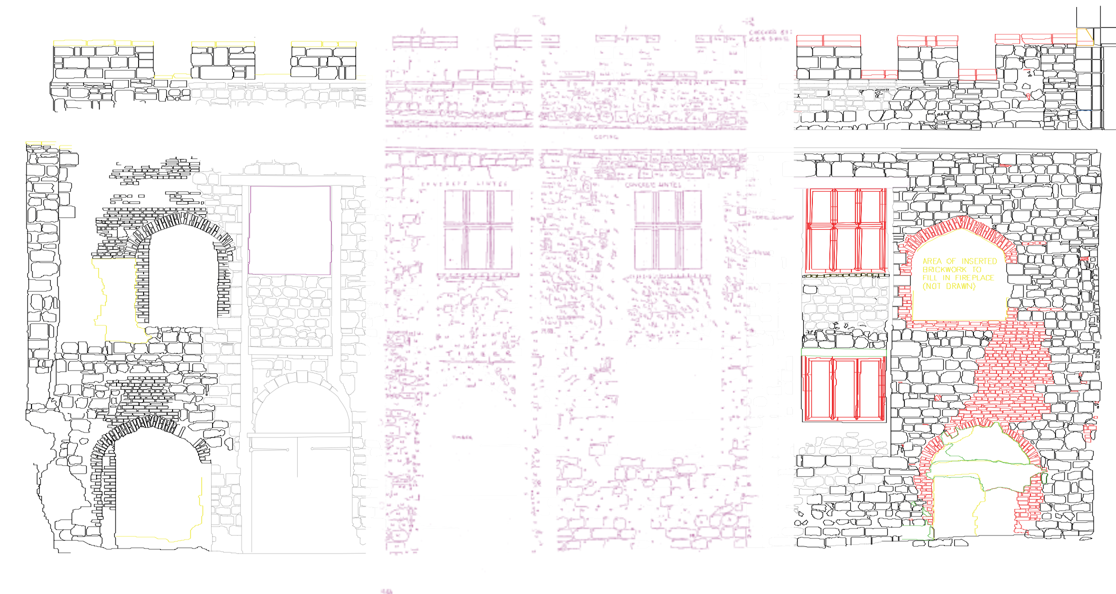
Fig 36
Detail of a hand-drawn overlay of corrections on a plot of photogrammetry: note the extent of the revision on the stones between the windows. The three-character codes on the stones record weathering and damage against a pre-set glossary.

Fig 37
An isometric view of photogrammetric data with digitised corrections recorded in two dimensions: in this example, photogrammetric UCS puts the wall face at an elevation of ten.



the finished product on the right and the hand-measured corrections in the centre as bold lines with the raw data shaded below. Note how the wall-head, which had been capped as a ledge within the ruin, was completely obscured at the time of the photogrammetric survey and had to be recorded entirely by hand. Note also how a number of stones that were either in shadow or otherwise indistinct in the photographs had to be redrawn. Typical problems included cracked stones being drawn as two separate stones by the photogrammetrist and the omission of small details, such as tiles used as packing. In many instances, the details could only be seen upon close inspection. Figure 36 shows the overlaid hand corrections and the primary photogrammetric data. While the building's exterior ashlar faces required fairly minor revisions, approximately 25 per cent of the fabric of the coursed-rubble interior faces needed some form of correction, alteration or enhancement.

In conclusion, the Battle Abbey courthouse project required a combination of photogrammetric and hand-survey techniques to create a product that not only satisfied the needs of the architects but also those of the building analysts and the Inspector of Ancient Monuments.



Opposite bottom
Fig 38
An isometric view of the interior of the Battle Abbey courthouse, as used on site information boards during excavations in 1993 and 1994.

Fig 39
A composite elevation of the Battle Abbey courthouse showing raw photogrammetry, hand-drawn corrections and the completed model.

5.2 Danson House: a measured drawing survey

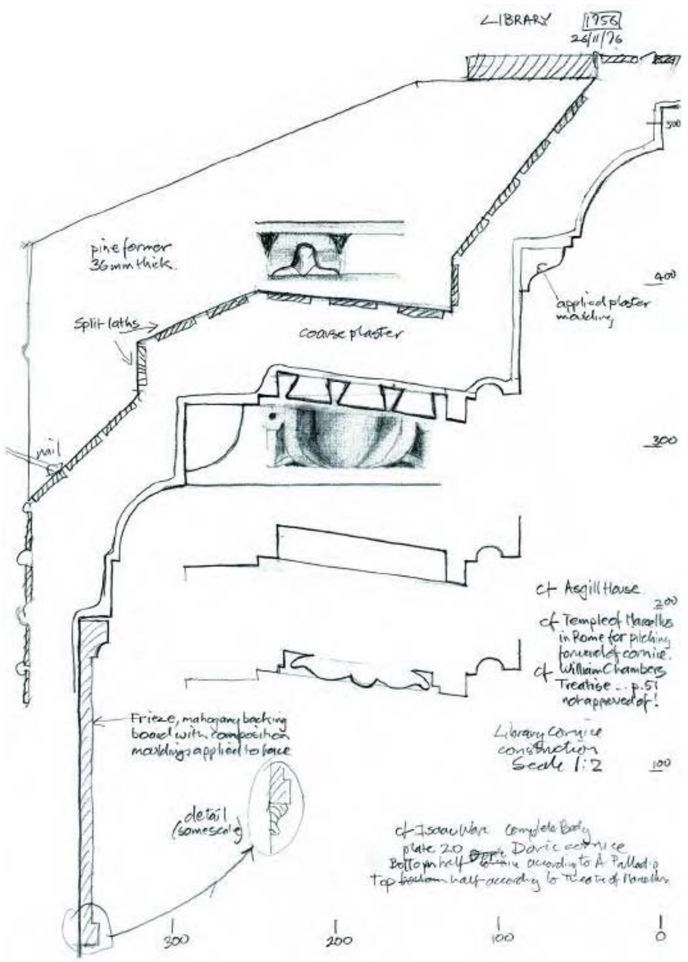
Danson House in Bexley was built between 1763 and 1766 to the designs of Sir Robert Taylor (1714–88). It is a prime example of a villa designed by a leading exponent of the Palladian movement in England. Much of the original detail survives and the house has been restored by English Heritage.

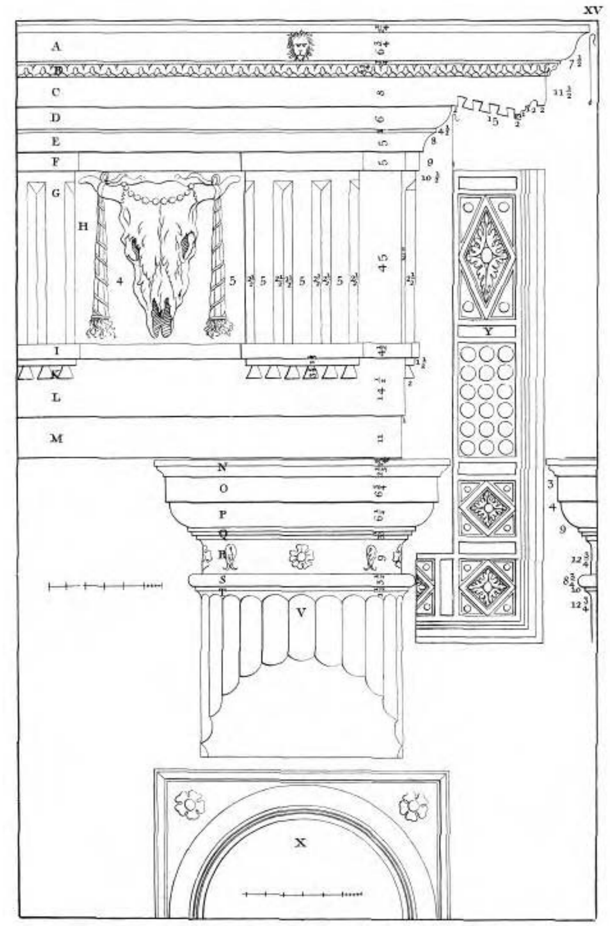
The library cornice (Fig 40) was drawn by hand, at a scale of 1:2, on site, on an A4 sheet of grid paper, by a practitioner working from a scaffolding tower (Fig 41). As a section drawing, however, it is a composite: at no point in the room was the cornice wholly sawn through and exposed in one single section. The drawing is therefore an assemblage of a set of observations made at various points around the room.

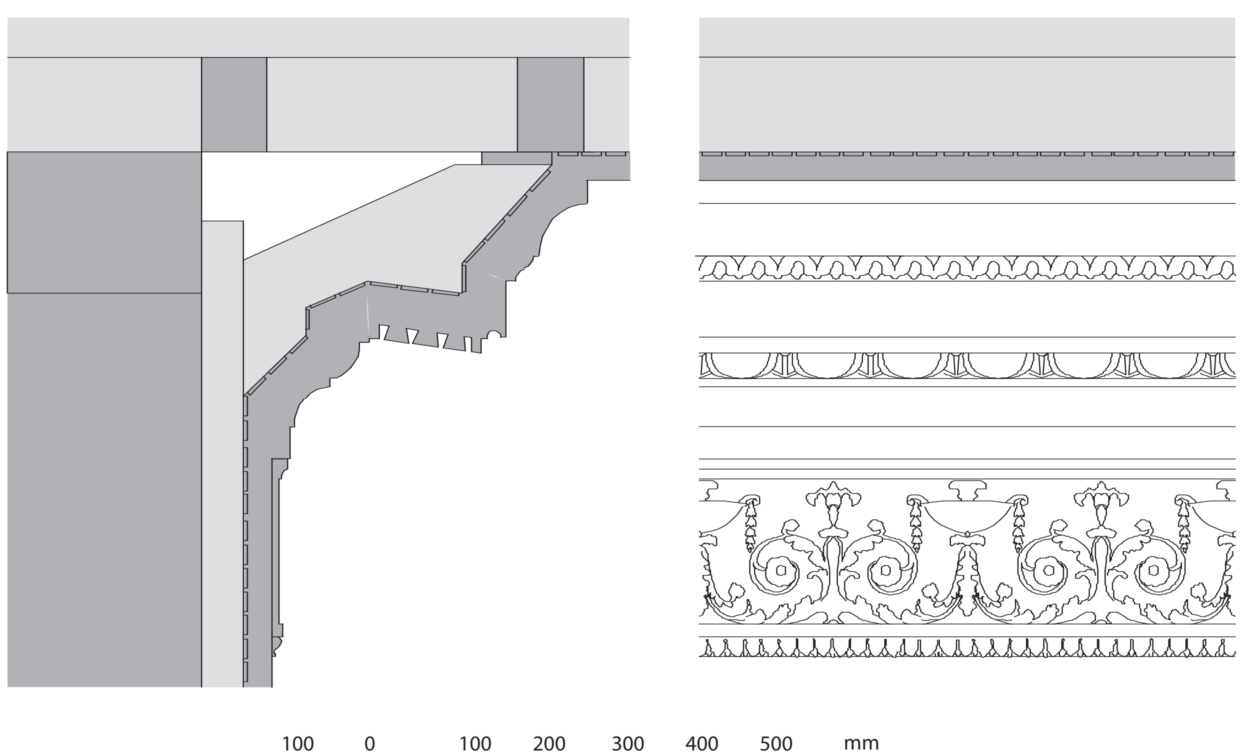
Besides the profiles of the plaster mouldings, the drawing records constructional details such as the lath and timber formers on which the cornice was run. Applied to the laths was a base coat of white lime plaster *c* 22mm thick (which included lumps of lime up to 8mm in size and some animal hair). A skim of white lime plaster was applied to the base coat. The finished plaster wall face was about 85mm proud of the brick wall face. This detailed construction information is significant in determining whether or not the cornice dates from the first fitting-out scheme within the room and thus is the work of Robert Taylor.

Fig 40
The plaster cornice and frieze in the library at Danson House.

The profile and proportions are important for the architectural historical analysis of the cornice. Comparison with drawings of similar cornices enables the identification of historical precedents and influences. The plaster cornice is of the Doric order and ultimately derived from the Theatre of Marcellus in Rome. This cornice appears, however, to have stimulated some







Opposite top left
Fig 41
Hand drawing of the same Danson House cornice and frieze.

Opposite top right
Fig 42
Palladio's drawing of a Doric cornice from The Four Books of Architecture.

Opposite bottom
Fig 43
The drawing of the cornice translated into a CAD detail drawing.

Above
Fig 44
A CAD section through Danson House showing the building as completed in c *1765 before fitting out. Here, the cornice drawing is included as a detail.*

Left
Fig 45
A CAD section showing the house after fitting out in c *1766: the library is the first-floor room with the bookcases. Note how the fitting out of the principal floor does not fit exactly with the masonry shell as shown in Fig 44.*

debate among those who illustrated it and Taylor's version at Danson is no doubt a personal interpretation. Sebastiano Serlio (1475–1554/5) illustrated the Roman cornice in *The Five Books of Architecture* (Book 4, fol 18; published in 1540), with the cavetto at the top, but with the mutules recessed and horizontal. The lower parts were also recorded very differently. It seems that Taylor took Andrea Palladio's (1508–80) model Doric cornice, based on the Theatre of Marcellus example and illustrated as Plate XV in Book I of Palladio's *Quattro Libri dell'Architettura* (1570) (Fig 42). He adhered to Palladio's model in all respects except for the projection of the mutule course and in the use of a cavetto in place of the greater cymatium. Isaac Ware (1704–66) reproduced his version in Plate XVII in his *A Complete Body of Architecture* (1756) and, it seems, like Palladio, considered the use of the cavetto at the top of the cornice to be an error based on a misinterpretation of Vitruvius's text. Sir William Chambers (1723–96), however, accepted the use of the cavetto but objected to the mutules hanging down. He reproduced the cornice with the ornament in the horizontal position.

This analysis demonstrates not only the importance of Palladio for the architect Robert Taylor and his generation, but also the ways in which Taylor felt it appropriate to interpret the Classical precedents.

The timber and composition frieze below the cornice is a 19th-century addition incorporating a repeated arabesque motif. On site, only essential dimensions were taken for this element. The detail was added later in a CAD package using simple rectified photography and the hand drawing as a control. The outline of the arabesque was then traced from photographs taken square-on (Fig 43).

This drawing forms only part of a detailed survey of the whole house. Once transferred to a CAD package it was simplified and used in several larger section drawings through the whole house (Figs 44 and 45).

5.3 Dauntsey Doom Board: the use of rectified photography

In October 1998 the English Heritage photogrammetric unit was approached by the historic buildings architect for the South West Region of English Heritage to provide a photographic record of the Doom Board from the church of St James the Great at Dauntsey, near Chippenham in Wiltshire.

Rectified photography was the survey technique chosen, as it provided a cost-effective, image-based method of recording the Doom Board before its eventual return and re-hanging within Dauntsey church. This survey method is ideally suited to flat, non-3-D surfaces such as painted oak boards.

The Doom Board now comprises 25 painted oak boards. At the start of the survey, rather than forming one complete unit, the 25 boards had already been separated, as they had been removed from the church to undergo conservation treatment. Some of the original boards were missing and others had suffered physical loss, principally from the edges, which meant that there was some uncertainty regarding the Doom Board's final arrangement. It was hoped that rectified photography could help determine the original layout. Rather than providing individual images for a manual 'cut and paste' exercise, it was decided to use digital rectified photography to assemble a 'virtual' montage that could be manipulated using a computer (Figs 46 and 47).

5.3.1 Recording issue

The 25 individual oak boards had been restored at a conservator's workshop in Corpusty near Norwich. They had been laid out on the studio floor in what was thought to be their correct positions. Limited working space meant that the original idea of photographing the whole arrangement of boards from above had to be discarded. Placing a camera vertically over a large body of work was neither practical nor safe for both the photographer and the boards, because of the risks of tripods or other surrounding objects slipping and dropping onto the boards.

Another difficulty was that of illuminating the boards evenly. The original idea of using the existing natural light coming through the workshop's skylights had to be rejected, as the light would be uneven and exposure would have to wait until there was sufficient cloud cover outside to minimise shadows and flare. In addition, the surfaces of the boards had been treated with what appeared to be a highly reflective varnish, which created a vast number of highlights when the boards were viewed from different positions. It was essential, therefore, that illumination for photography could be fully controlled.

5.3.2 Photographic method

Bearing the above problems in mind, it was decided to create a small photographic copy set-up in the conservator's workshop and to photograph each board separately.

Fig 46
One of the 25 boards that make up the Dauntsey Doom Board, showing a significant loss of fabric.

Fig 47
The Dauntsey Doom Board laid out at the conservation studio.

Two electronic flash units were used and fitted with soft boxes. This provided the ability to control what light was falling on the subject and at what angle, reducing the chances of highlights reflecting off the shiny varnish finish. Using a professional flash system also provided a colour consistency of 5500K (Kelvin), the colour temperature of daylight. This matched the colour temperature of the film and would provide accurate results. To give the darkroom printer or the digital-scanning operator a reference from which to work, an industry-standard Kodak colour chart was placed in each photograph taken.

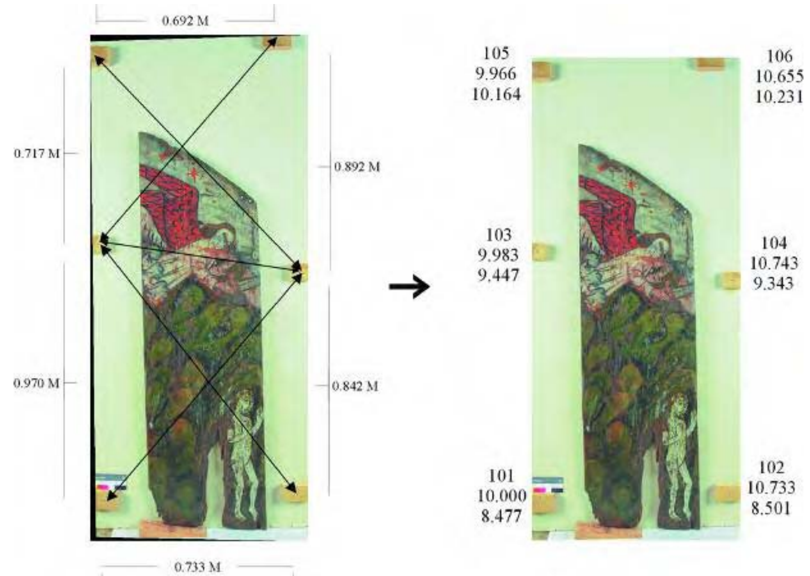
A medium-format, 120-roll film camera with a 90mm lens was used for the photography. Given the circumstances this was considered the most appropriate format for the project because of its greater flexibility over the larger 5in × 4in format. In addition, the final enlargement factor, from negative up to final 1:10 print scale, was also well within the capability of the arrangement, making it possible to have imagery without any loss of definition.

A high quality film was chosen, both for its ability to represent neutral colour – providing no bias to any dye – and for its good batch quality in colour consistency.

5.3.3 Control method

To provide an accurate scale to the final rectified images, the individual boards needed some form of control data. Placing targets on the surface of the painted oak was not possible because this might damage the boards. It would also have been very time consuming for a surveyor to observe detail points on each of the 25 boards.

Instead, a large plain-background panel was used as a frame and, by attaching to it small blocks of wood that were the thickness of Doom Board itself, one common set of control data was provided to each of the panels as they were consecutively placed within the frame. Small 10mm diameter, black and white self-adhesive targets were placed on each of the six small wooden blocks. The distances between each of these targets were then measured in two braced, quadrilateral arrangements, using a steel tape. Then, using simple trigonometry, 2-D co-ordinates were computed, based on a reference value of ten for the lower left-hand target; this ensured that all the values would be positive (Figs 48 and 49).



Above right
Fig 48
In order to be photographed, each board was placed on a plain panel on which six control targets had been fixed. Simple trigonometry was used to determine the two-dimensional co-ordinates for each of the six targets.

Above
Fig 49
On the left, the image lists the measured distances between points that were used to compute the 2-D co-ordinates. On the right, the image shows the control points numbered and the calculated co-ordinates for each point. These co-ordinates were then used in the rectification process.

5.3.4 Rectification and digital manipulation

All exposed film was processed through a quality-controlled professional laboratory to ensure consistency in the colour reproduction of the dyes in the base emulsion. To provide digital copy, each negative was scanned and copied to a high-quality photo-CD. This enabled the digital image files to be loaded into image manipulation software. The rectification of each image was carried out using professional photo rectification software (Fig 50).

Using the computed 2-D co-ordinates, each image was digitally rectified on screen and a scale was attached to each of the digital files. When all 25 images had been individually rectified they were imported into imaging software for cropping, balancing and montaging. Before the final montage was created, each one of the rectified images was imported into a CAD package for viewing and editing. This facility was used with advice from the historic buildings architect and the project architect to help determine the most appropriate board arrangement, based on the visible evidence.

Fig 50 The digital rectification process..

Fig 51 The final montage of the rectified image.

The imaging software was chosen because it provided the user with the facility to edit the background and leave it transparent, thus enabling several different layers of information to be edited. Each one of the 25 doom boards was assigned its own layer, which made it simple to rearrange the boards and position them accurately to form the final montage as shown in Figure 51.

5.3.5 Conclusions

This work was completed to a very high standard and the end product, importantly, was what the conservation team required. The control used, although provided by simple steel tapes, was economic, robust and precise enough for the rectification process, and had no impact on the fragile boards. Since this work, improvements have been made on colour control by adding an industry standard colour chart into photographs. It is apparent that people with limited knowledge of the overall photographic process have little idea of what makes an accurate record – for example, there is an assumption that available natural light is adequate to illuminate the work. As in most location work, the photographer has to adapt to the surroundings, especially when the image is required for the conservation process and to provide a record for the national archive.

5.4 Measuring the Iron Bridge

The Iron Bridge at Coalbrookdale (Fig 52) was scheduled as an Ancient Monument in 1934 and is the centrepiece of the World Heritage Site designated by a United Nations Education, Scientific and Cultural Organisation (UNESCO) charter in 1986. The bridge is the world's earliest major iron span and was the prototype for iron bridge construction. It is of great importance as the first structure to use iron on an industrial scale and the manufacture of its components is a unique example of the quality-controlled production of iron as a building material in the 18th century.

The bridge is constructed of large cast-iron parts (the largest weighing up to 5.5 tonnes), which were cast, positioned and fitted in 1779 under the direction of Abraham Darby III (1750–91), master iron-founder, and Thomas Gregory (dates not

Fig 52
The Iron Bridge at Coalbrookdale. This was the world's first major iron-span bridge, erected in 1779 under the direction of Abraham Darby III (1750–91).

known), his pattern-maker. The form of the bridge is derived from a design by Thomas Farnolls Pritchard (1723–77), the architect directed by the bridge commissioners in 1776. There is no surviving copy of Pritchard's drawing other than early scheme drawings for iron spans, so it is an open question as to how much of the erected structure is from Pritchard's design and how much is a result of foundry pattern work. The historic central span of cast iron is 30.12m long. It comprises five frames supporting a roadway of 42 cast deck-plates. The span is an arch of a near-perfect semicircle standing on stone abutments. The deck rises at an angle of approximately 5∞ to a shallow arc joining the two-pitched sides of the deck.

In 1999, as surface corrosion had become extensive, the bridge was in need of painting. It was also found that there had been some loss of the bearing between the deck-bearers and the deck, which required consolidation.

5.4.1 Metric survey requirement

The proposed works needed metric survey drawings for scaffolding design, marking-up the painting regime and recording repairs. Metric survey was also used for the following purposes:

1 To verify the historic 1977 photogrammetric survey (although this survey was incomplete because there were obscured areas in the photographs and the opportunity was taken to use the work in the new survey).
2 To enter data from archaeological investigation on to 1:50 ink-on-plastic photogrammetric plots in order to provide a precise base for recording the type and phase of the bridge components in two dimensions.
3 To acquire a better understanding of the structure, as there are many gaps in our knowledge of both the design and construction phases of the bridge, and as the 3-D record enabled theories to be tested against true-to-scale information.
4 To provide visitors with virtual and on-site interpretation of the bridge through the use of 3-D survey data and high-resolution CAD models, thus enabling them to observe the structure from different viewpoints.
5 To record the repair histories of the bridge components in a 3-D framework so as to enable the survey data to be used as a GIS for informing future projects.
6 To map the twists caused by post-erection deformation, thus providing a stress analysis for the bridge and enabling locations of future failure to be identified.

The structure had undergone a number of movements since its erection in 1779. The rotational thrust between the abutments and the pressure of the unconstrained stonework led to a rebuild of the approach arches in 1821, and in 1972–3 below-water ferro-concrete retaining work had to be emplaced because of the continued movement of the footings. As a result, the shapes of the frames spanning the river have been distorted. Survey was needed to record the frames in their present state so as to enable them to be monitored over time and for any future movement to be understood.

A number of the original castings had cracked or snapped as a result of the stresses just described. The failure and subsequent repair or replacement of components revealed that much of the movement take-up had occurred prior to 1973. The snapping of the radials on the south side of the span, the compression of the chords of the main ribs and the displacement and twist across the deck were all recorded to a consistent 3-D positional precision of ±25mm for the model and ±10mm in the photogrammetric wire frame.

5.4.2 Survey techniques

Control:
A prerequisite of producing a complete survey of the bridge was the use of a common control network. Thirteen stations were set out on an adjusted traverse. These were used to ensure that the data produced by the different survey techniques were correctly positioned. Control for photogrammetry required the stations to be occupied for the recording of 600 control points on the bridge. Observation was carried out by two-point intersection to detail points on the structure rather than marked targets.

Metric survey methods:
The Iron Bridge presents a number of problems to the surveyor, including the need for a wide range of scales from 1:50 to full size. Additionally, line-of-sight obstructions and access restrictions affected all the applied techniques, and lighting and vegetation presented difficulties for photo-based techniques. When access was possible by scaffolding, TST and hand-survey techniques could be used. Nevertheless, gaps in the data set remained. Filling these gaps provided the team with an opportunity to evaluate the performance of laser scanning when applied to the rigorous levels of precision required for the survey of an historic structure of this kind.

Photogrammetry:
Stereo photography for photogrammetry was acquired from camera positions on the riverbank and also under the bridge at the footings, lit by available daylight. Vegetation obstructing sight lines from the riverbank and obscuring the retaining facades required the supplementary use of historic (1972) stereo photography. Limited access, poor lighting and near-camera obstructions obscured the soffit of the span and meant that there was no cover of the soffit at the centre of the span (Fig 53). Two metric cameras were used, one with a 100mm lens, at a range of approximately 40m and another with a 300mm lens for ranges exceeding 40m.

The wire frame is 3-D but rarely plots all the possible edges of the components because of line-of-sight obstructions, poorly lit imagery or indistinct edges. The consistency of precision in the wire frame is an inherent property of photogrammetry. Note the soffit of the deck as depicted in Figure 53: there is little or no information here because of the deep shadow in which the soffit lay at the time of photography.

TST:
When access by scaffolding was possible, a reflectorless TST was used to fill in the gaps in the photogrammetric wire frame. Stations were set up on the scaffolding between each frame and ties to the photogrammetric wire frame were made by resection to detail points. By using instrument set-ups under the deck, gaps could be infilled at close range. All the TST data was recorded in real-time into CAD software on a field computer (Fig 54).

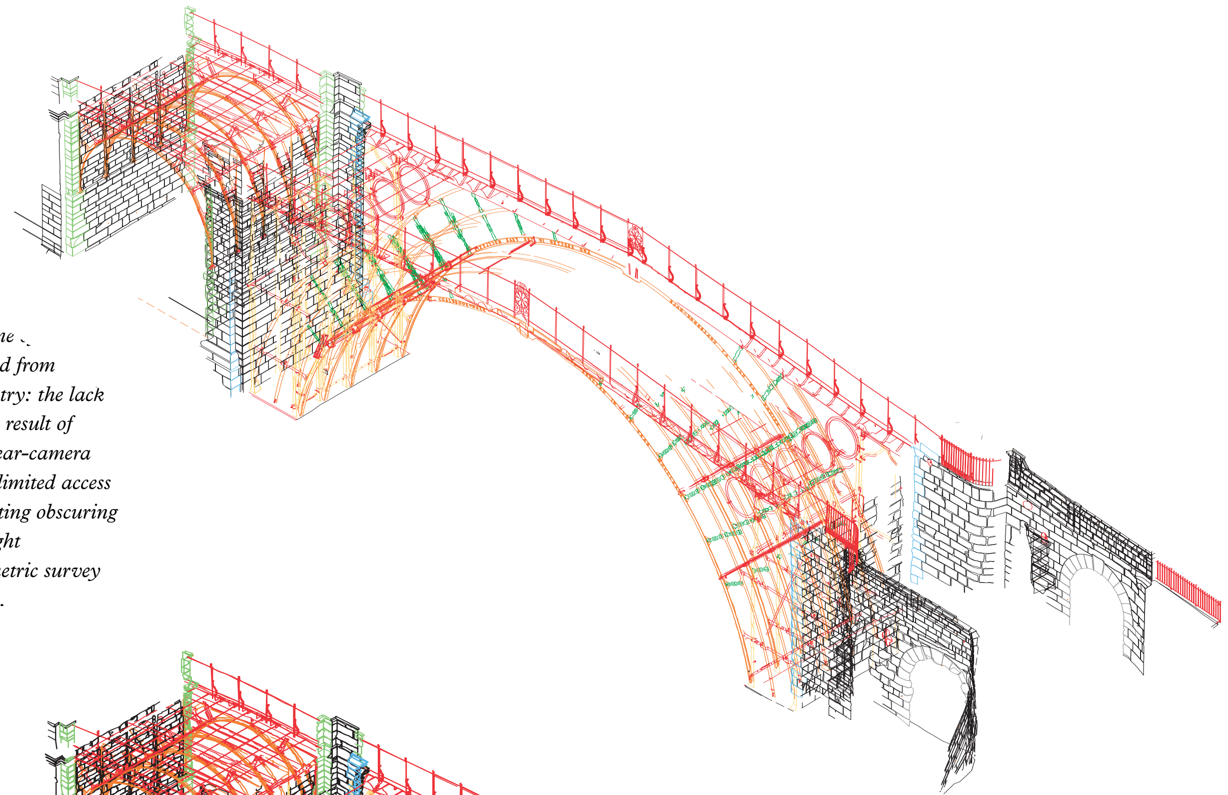


Fig 53
The wire frame ., Bridge, plotted from photogrammetry: the lack of cover is the result of vegetation, near-camera obstructions, limited access and poor lighting obscuring the lines of sight (photogrammetric survey by PCA Ltd).

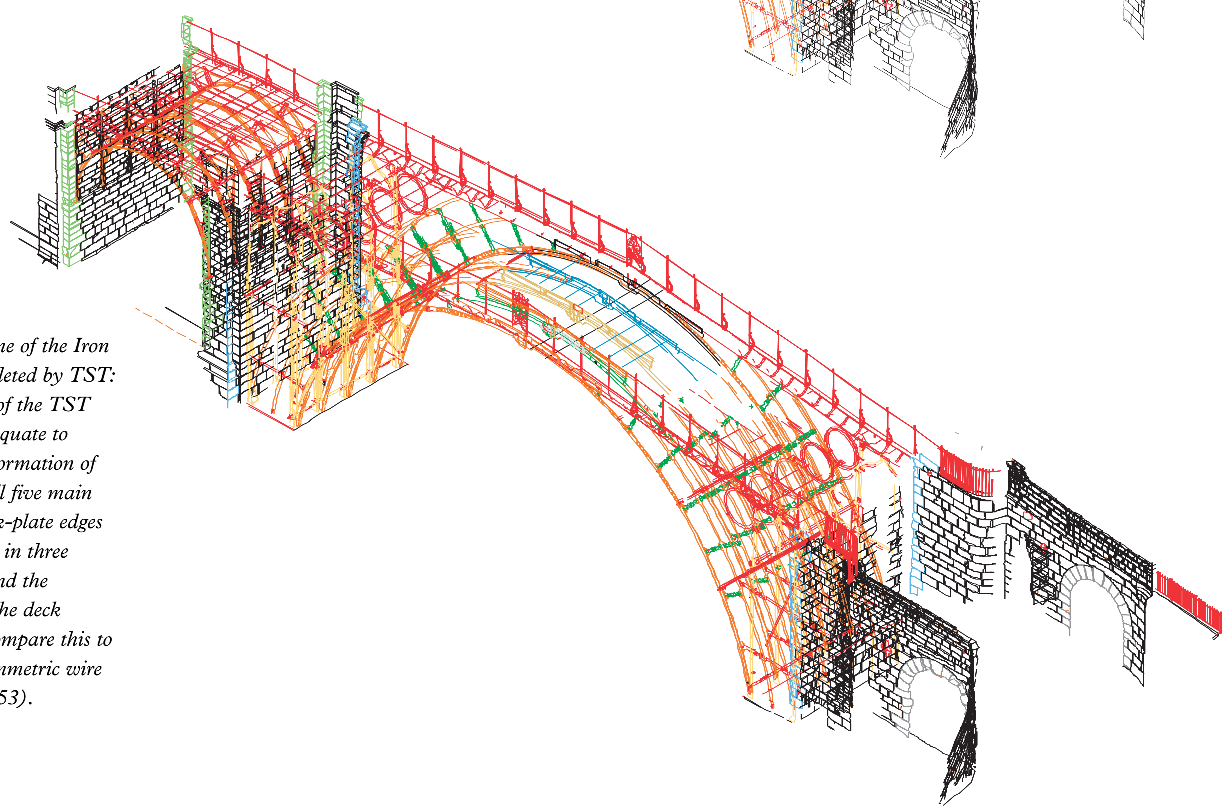


Fig 54
The wire frame of the Iron Bridge, completed by TST: the precision of the TST work was adequate to model the deformation of the arcs for all five main ribs. The deck-plate edges were digitised in three dimensions and the distortion of the deck recorded. (Compare this to the photogrammetric wire frame in Fig 53).

Isometric sketches and narrative photography:
Isometric sketches were needed to record and understand the fitting of the jointing and the engineering detail of hidden parts that were not visible in the elevation drawing (Fig 55). Narrative close-up photography was also taken of all of the joints and indexed by component.

Laser scanning:
Laser scans were taken to attempt to infill the deck soffit not mapped by TST or photogrammetry. The point cloud was modelled into CAD surfaces using automated surface extraction software. The laser scan was unable to supply any edge definition of components that could be generated to the required tolerance. The main value of the data was to add patches of information on the surfaces between the wire frame edges and to determine the surface profiles of the lower parts of the main ribs. The data received from the laser scan were generally of poorer utility than those produced by photogrammetry.

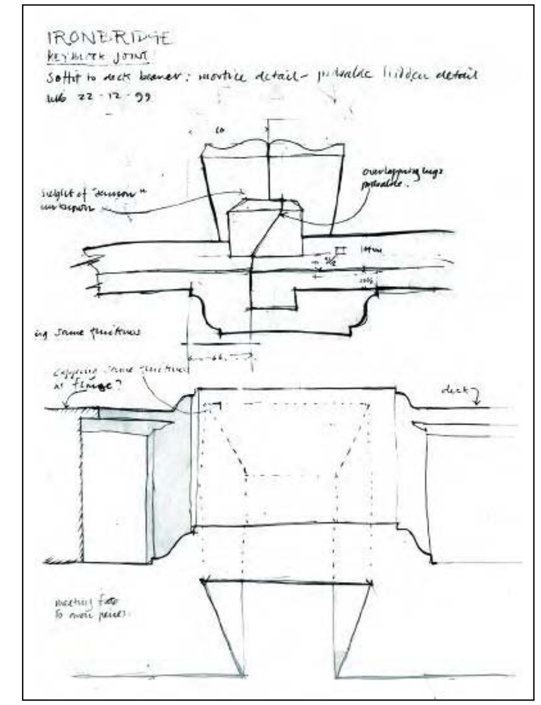
The point cloud from the laser scan (Figs 56 and 57) could be used only for surface interpolation. The mapping of edges was not possible because of the low density of the point cloud and the skewing of distance values caused by multiple signal reflection.

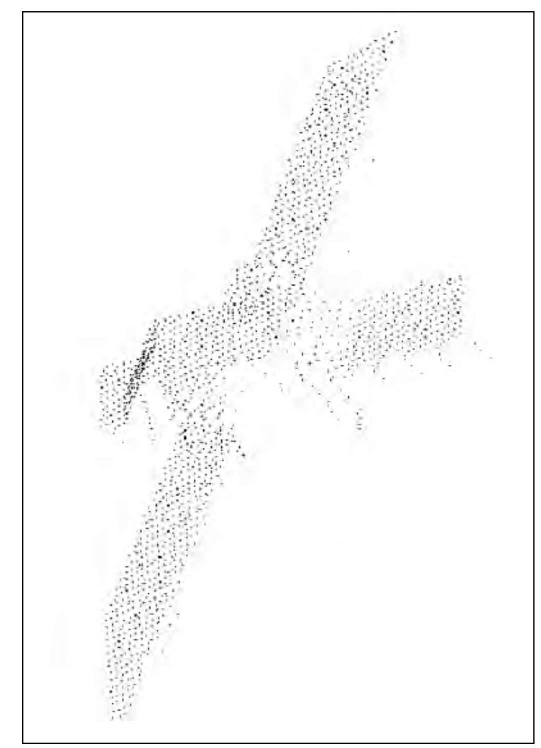
Measured drawing:
2-D details of the bridge's joints were recorded on site by plotting the measured detail directly onto 1:50 scale elevation plots. To maintain vertical control for this, string-levelled lines were used to transfer data from plot to plot. The pencil annotations were then inked in. Ironbridge Gorge Museum Trust Archaeology, under the direction of Shelley White, plotted evidence for the sequence of casting and assembly onto ink-on-plastic plots supplied from photogrammetry. The plotted evidence was subsequently used for the archaeological analysis.

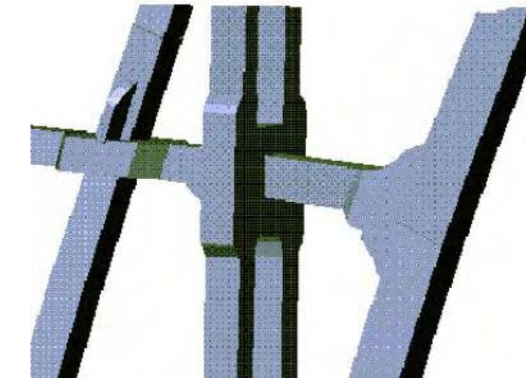
5.4.3 Constructing the solid model from the wire frame CAD model

Since the wire frame from photogrammetry and TST survey was built on a common control system and CAD platform it could be used to form and fit solid components in true 3-D positions. It was decided to use solid, rather than surface, modelling for the following reasons:

1. edge extraction – a solid model enables the extraction of line drawings without disruption by surface meshes;
2. file size is reduced compared to the surface model equivalent;
3. component fitting and counterpart modelling is possible – the fit between parts can be used to create the edges of components;
4. and finite element analysis is possible.





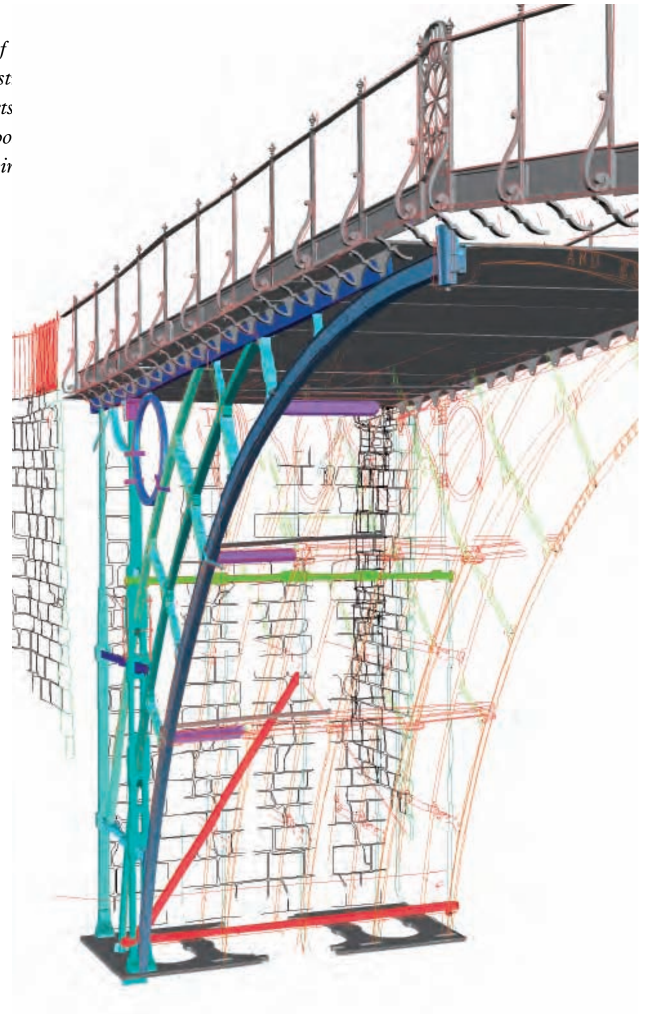


Far left top
Fig 55
Site sketch of the Iron Bridge crown joint, showing detail: the sketch records the hidden halved dovetail tenon and its counter part on the crown bearer, revealed by inspection.

Far left bottom
Fig 56
The point cloud supplied by the laser scanning of the Iron Bridge: the point density at a 10mm post spacing was insufficient for high parity modelling (laser scan by UK Robotic Ltd).

Above
Fig 57
Automatic surface generation from the laser scan point cloud of the Iron Bridge: the mouldings of the castings have been corrupted beyond recognition. The generated surfaces are seen here exported into CAD (laser scan by UK Robotic Ltd).

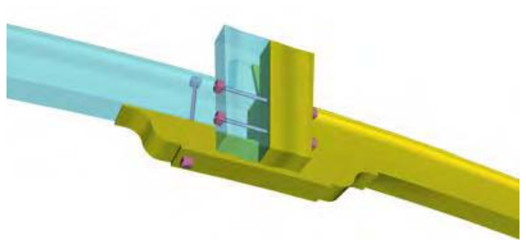
Fig 58
The solid model of
Bridge under const
the railing supports
been copied into po
bounded by the wi



By building up closed regions from the wire frame, solid parts were extruded into their true co-ordinate positions in space. Where possible, an attempt to use repeat components was made to test the fit of unseen housings. Most of the joints have generous passing tolerances, so it was surprising to find that many parts could not be fitted in this way. Most of the radial links between the ribs are one-offs, suggesting that many castings were made to retro-fit locations – that is, to fit the spaces left in the structure during construction. The distortion of the main ribs is such that a reflection from one quadrant to its opposite is not possible. The simple arc sections used for the ribs are subject to tilt and twist, and careful interpolation of the wire frame was needed here to develop solid components (Figs 58 and 59).

Regarding modelling conventions and parameters, modelling the bridge required a compromise between model integrity and CAD performance. The bridge comprises some 1,420 cast parts (excluding fixings and fasteners). To model all the parts and their variants as full-size replicas would have generated a file size of approximately 500 megabytes, unusable without extensive computer resources at the time. It was decided that there should be a tolerance of up to 35mm surface-to-edge variation to economise on surface generation for the solids used. Where it can be inferred that parts have a path through each other, such a path has been interpolated in the model. Many joints are indistinct as they have been caulked with molten lead to fill voids and the internal spaces of the joint housings can only be estimated. As with simpler CAD models and drawings, layering was used to separate the data by location, part name and phase.

Fig 59
The CAD model of the Iron Bridge replicates the joint and demonstrates the fixing method used. The joint's overall position and orientation were determined from the photogrammetric wire frame.



5.4.4 Insights and discoveries through metric survey data

Evidence of industrial techniques:
The detailed investigation required by the survey showed that various industrial processes had been used to construct the bridge. Evidence was found for the following:

- the use of two casting processes in the manufacture of the bridge components, ie 'Swept-up casting' and 'Closed casting';
- the re-use of counterpart patterns for mortises and passing moulds;
- the use of retro-fitted parts;
- the development of fixing technologies;
- the orientation and sequence of casting;
- and variation of pattern quality.

Erection sequence:
The CAD model can be used to test erection theories. For example, by fitting views of the model to the 1779 sketch by Elias Martin it is possible to attempt to re-create the sequence of assembly.

Assessment of pre-photographic images/drawing regression study:
Comparison between a matched perspective view in an engraving by William Ellis after M A Rooker (*c* 1782) and the CAD model (Figs 60 and 61) reveals the omission of frame C details. This omission adds to the evidence that the engraved view was prepared from design drawings rather than from the structure itself.

Fig 60
The Cast Iron Bridge near Coalbrookdale, *an engraving by William Ellis after M A Rooker, dated 1782: the 'missing ribs' are shown even though they were not in place until 1791 and the frame C casting error is absent, suggesting that this is a view worked up in the studio, probably from design drawings (© Ironbridge Gorge Museum Trust; 1978.78).*

5.4.5 Effectiveness of survey methods

Photogrammetry is the most reliable method for mass 3-D data capture, but it can be compromised by the image quality of the stereo pair. The production of the wire frame used in the survey required the provision of a detailed brief for the contractor, who was chosen on the basis of having carried out previous work of this kind. The selection of edges to produce a good 3-D wire frame for complex historic structures needs to be based on experience underpinned by a sound architectural knowledge.

The infill by TST matched the wire frame integrity from photogrammetry. Real-time CAD data collection made data selection and checking possible to a high order of precision and observational

Fig 61
View of the CAD model matched to the view of the Iron Bridge shown in Fig 60 and revealing the casting error on frame C.

accuracy. The selection of edges was informed by real-time checking of the wire frame on site.

Laser scanning did not supply precise edge-defined modelling of the structure, as the point cloud was of insufficient density for the selection of edges. This was exacerbated by automated feature extraction, which resulted in poorer data than that from photogrammetry at the large (1:20–1:10) scales needed to replicate the engineered fit of the bridge components.

The construction of a 3-D model enables greater use of the survey data. The mechanical constraints of the bridge can be investigated, and component integrity and failure patterns tested. The 3-D model also gives greater scope for the presentation of a well visited site such as the Iron Bridge; it can be used for virtual reconstruction, construction animations, showing indications of historic ad hoc design and explaining the conservation and analytical work that has been undertaken.

5.4.6 Interdisciplinary approaches

Type-specific knowledge is essential for specialist recording: the recording of variations in components, their displacement and other factors should be informed by a knowledge of the design constraints, methods used and known repair regimes. In this case, in-depth knowledge of the history of the bridge focussed the survey work on specific details and areas, which made it possible to produce animated construction sequences from the 3-D model.

5.5 Peterborough Cathedral nave ceiling

The great medieval nave ceiling at Peterborough Cathedral dates from between 1210 and 1230 and is the only 13th-century painted wooden ceiling to survive *in situ* in the UK (Fig 62). The ceiling is 62m long, 11m wide and canted on each side. It is constructed from overlapping oak boards, held in place by nails driven into joists from below. Attempts over the years to reinforce these fixings have increased the rigidity of the ceiling structure, preventing the natural movement of the wood. This, combined with recent environmental conditions in the cathedral, has caused new structural problems, such as the loosening of some of the original nails and the splitting of boards. The conservation project was aimed at securing the long-term survival and security of the ancient painted boards in their present condition.

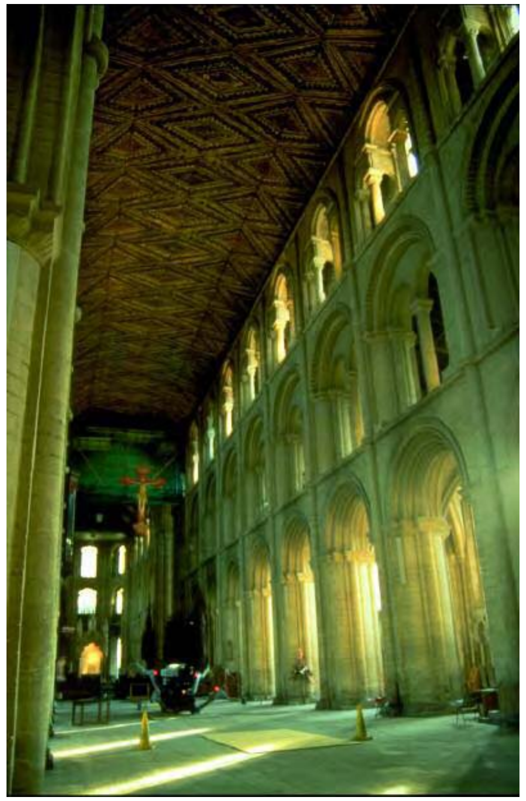


Fig 62
View of Peterborough Cathedral nave (© Julian Limentani).

In 1994 English Heritage was approached to provide advice to the Architect to the Dean and Chapter of Peterborough on the survey requirements for the proposed conservation project. Consultation focused on the potential use of photogrammetric techniques to provide the base survey data for both the architects and the conservators to plan and carry out the required treatments. Discussions initially centred on the production of a suitable specification for a photogrammetric outline survey of the entire ceiling for the Dean and Chapter, which they could then use to procure the required data themselves, through a contractor. It soon became apparent, however, that the amount of detail was such that a scaled photographic montage of the whole ceiling would also be required. It was recognised that this project would provide an ideal opportunity to test the application of digital photogrammetric techniques, in particular orthophotography, in a conservation environment. As a result the English Heritage Metric Survey Team became directly involved in the work.

5.5.1 Survey control

At the time of the survey, in December 1996, no fixed survey grid existed around the cathedral. Twenty temporary survey stations were therefore set out on a local grid on the triforium, from which observations to control stereo pairs could be made. Using a TST, the traverse from the triforium was brought up into the roof space, providing a common 3-D control system. Main stations were laid out along the central walkway of the roof and satellite stations were placed to give a line of sight down the sloping panels to the inaccessible wall-head. It was essential to use the same control system for the roof survey as for the ceiling.

To enable each of the 22 stereo models to be orientated in an analytical stereo plotter or a digital photogrammetric workstation, a minimum of four control points per model was required. Owing to the difficulty of placing plastic targets on the ceiling, it was decided to use points of detail, even though these would not provide the same clarity of pointing and hence level of accuracy as a target, and would also take longer to observe. The wide platform at triforium level was used for surveying the control points by intersection, as it provided both an excellent view of the ceiling and reduced the need for any extreme vertical angle observations (Fig 63). To make it possible to carry out the intersections effectively, colour prints were made from the stereo photography and marked up directly on site, as detail points were selected. A total of 85 points of detail were co-ordinated. This meant that there were up to six points available per model. Normally only four points per model are required so these extra control points helped to ameliorate the reduced accuracy that was a consequence of using solely detail points.

5.5.2 Stereo photography

The cathedral ceiling is 25m above ground-floor level. In order to acquire stereo photography of a suitable negative scale, it was necessary to use either access equipment or a camera with a telephoto lens. The use of access equipment was rejected for two reasons: first, there was the physical difficulty of bringing a scaffolding tower or hydraulic lift into the cathedral; and second, the photography had to make use of available light, since artificial methods would not have given adequate illumination over the whole ceiling. The long exposure times thus involved made the use of access equipment impossible, as it would not have been sufficiently stable. The decision was therefore taken to use a metric camera with a telephoto lens for the photography.

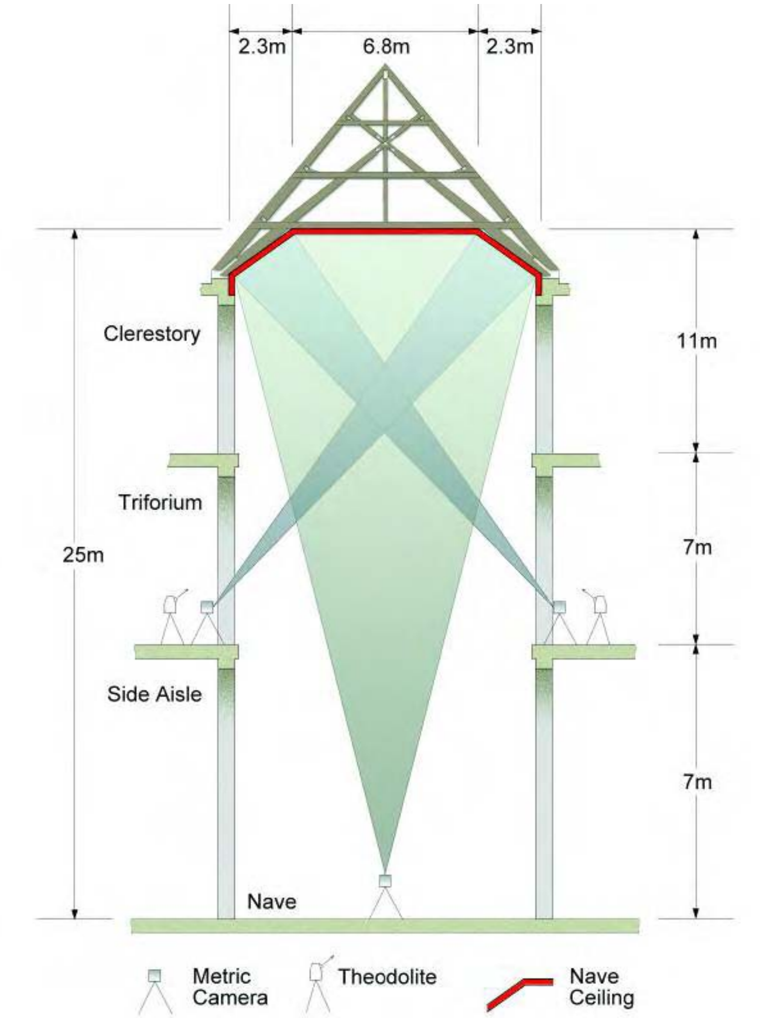


Fig 63
A diagram showing the camera and theodolite set-up positions that were used to take and control the stereo pairs for the survey of Peterborough Cathedral.

The 5in $\times$ 7in format and 300mm lens of the camera meant that the entire width of the ceiling could be covered in one photograph taken from the ground floor (Fig 63). The resulting negative scale of approximately 1:80 was sufficient to make possible the production of drawings at 1:20, or even 1:10. The camera and tripod were mounted on a 'dolly' and wheeled

Fig 64
A stereo pair of the nave ceiling in Peterborough Cathedral.

Fig 65
A photogrammetric plot of four of the 13th-century ceiling panels in Peterborough Cathedral: the plot contains ferramenta *and painted detail.*

Opposite page
Fig 66
The plan of the roof structure of Peterborough Cathedral in contact with the ceiling (left) and the orthophotograph of the painted boards (right). Both are as seen from below.

down the centre of the nave, making possible a run of 23 photographs and thus 22 stereo models (Fig 64). In addition to this ground-based photography, stereo imagery was taken from the triforium using a 5in × 4in format metric camera with a 100mm lens, in order to cover the two canted side sections of the ceiling, although in the end this was not required owing to the excellent coverage provided by the ground-based photographs.

5.5.3 Photogrammetry

The initial requirement of the project was a set of photogrammetric line drawings (Fig 65). These were to be plotted on A1+ sheets at a scale of 1:20 and were to cover the architectural detail within the first 7m of ceiling at the eastern end of the nave, which was to be the extent of the first phase of conservation works. In addition, a set of A3-format drawings at the larger scale of 1:10 were needed during the actual conservation works on site, to enable all the visible structural features – such as nail heads, screw threads and tie bolts, as well as the painted detail itself – to be referenced.

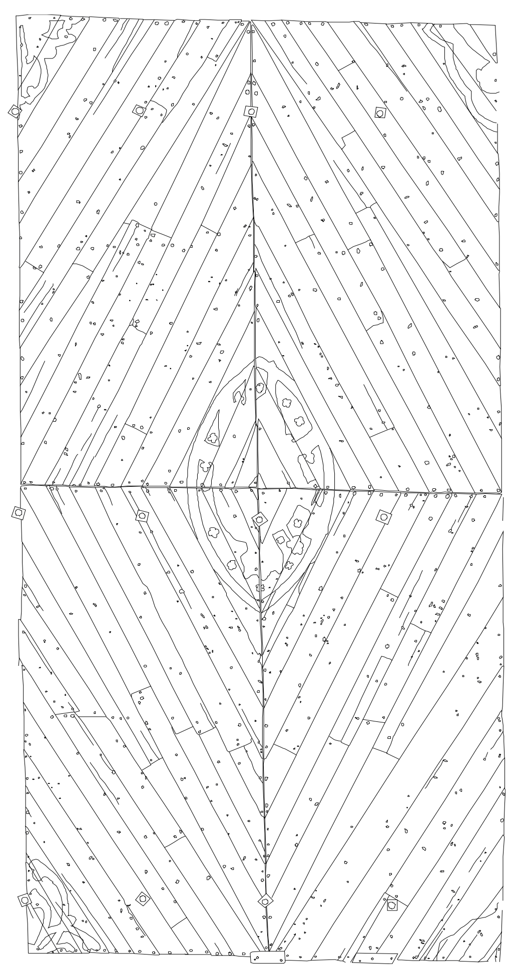
In discussion with the conservation consultant and architect, the precise level of detail for the survey was agreed. All of the detail was recorded according to the *Metric Survey Specifications for English Heritage*, although the CAD layering convention recommended in that publication was reduced down to three layers – boards, fixings and painting.

During this initial plotting work some interesting problems arose.

The first was how best to represent each of the oak boards that made up the actual ceiling. As each board overlapped its neighbour, it was impossible to record accurately all four edges of the lower face, as one edge was usually hidden from view. It was therefore decided that where part of a board was hidden by the overlap of another, only the visible edges would be plotted, as an unclosed 3-D polyline.

A second problem was that as some of the painted details were difficult to interpret successfully as lines, particularly when viewed at high magnification, it was decided to plot these only as basic outlines and to infill these outlines with scaled photographic images.

Using this initial plotting work as a benchmark, an accurate estimate was provided to the architect of the cost involved in photogrammetrically processing the remaining 55m of ceiling to the same level of detail, using the stereo photographs and survey control data provided by the English Heritage Metric Survey Team. This information was used by the Dean and Chapter to procure the rest of the plotting work.



5.5.4 The use of orthophotography

As noted above, little of the painted detail was to be recorded as line work. Instead, a scaled photographic image was to be used, and it is here that the application of digital photogrammetric techniques, in particular the orthophotograph, was to become crucial to the documentation of the project.

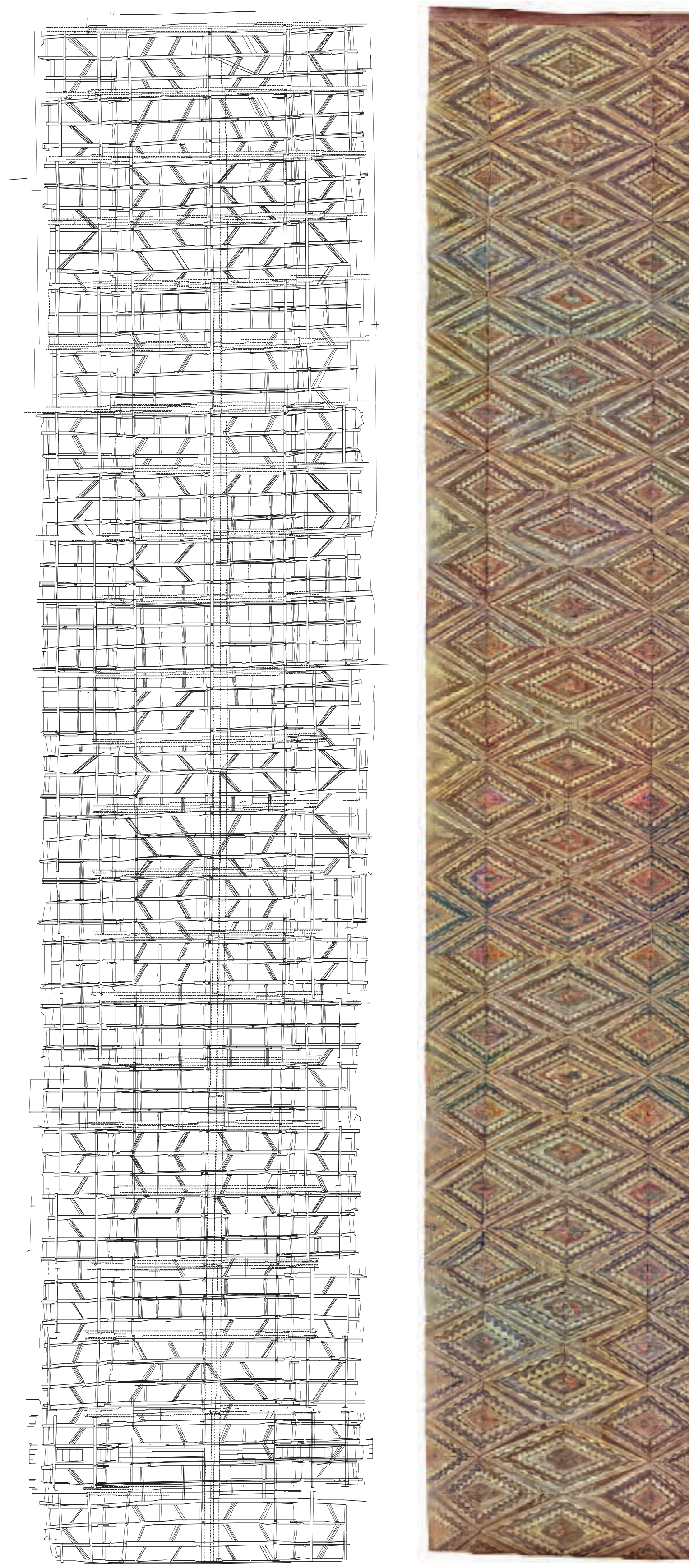
The colour negatives were scanned at 22.5-micron resolution, using a photogrammetric scanner, producing files of *c* 120MB each. These were imported into a digital photogrammetric workstation, and processed to form a digital orthophotograph of the ceiling at 5mm pixel resolution with a file size of 90MB (Fig 66).

The major difficulty encountered during this part of the project was the colour balancing of the 23 colour images used during the production of the orthophotograph. Even though geometrically correct scans were used, the slight variations in exposure within each colour negative caused by reliance on natural light appeared to have upset the automated scanning process usually employed during the scanning of aerial imagery. This resulted in individual scans that were incorrectly colour balanced and that, when joined together, produced a very fluctuating colour image, even after processing with image processing software. Eventually the photographs were re-scanned using a proprietary photo-CD system in an attempt to produce colour images that could be evenly joined together.

Extracts from the complete orthophotograph were provided in digital form for the conservators working on the scaffolded ceiling. These images were imported into imaging software running on laptop computers to provide a backdrop to the line drawings, which were converted from the DXF format. The conservators annotated the drawings while on site (Fig 67).

5.5.5 TST survey

During the conservation work the team needed to match detail from below the ceiling to the roof structure above. The roof structure consisted of 19th-century timber trusses holding up the original medieval timbers. Owing to the inaccessible nature of the roof space, and because there was no clear line of sight for image-based survey, a TST survey was undertaken.



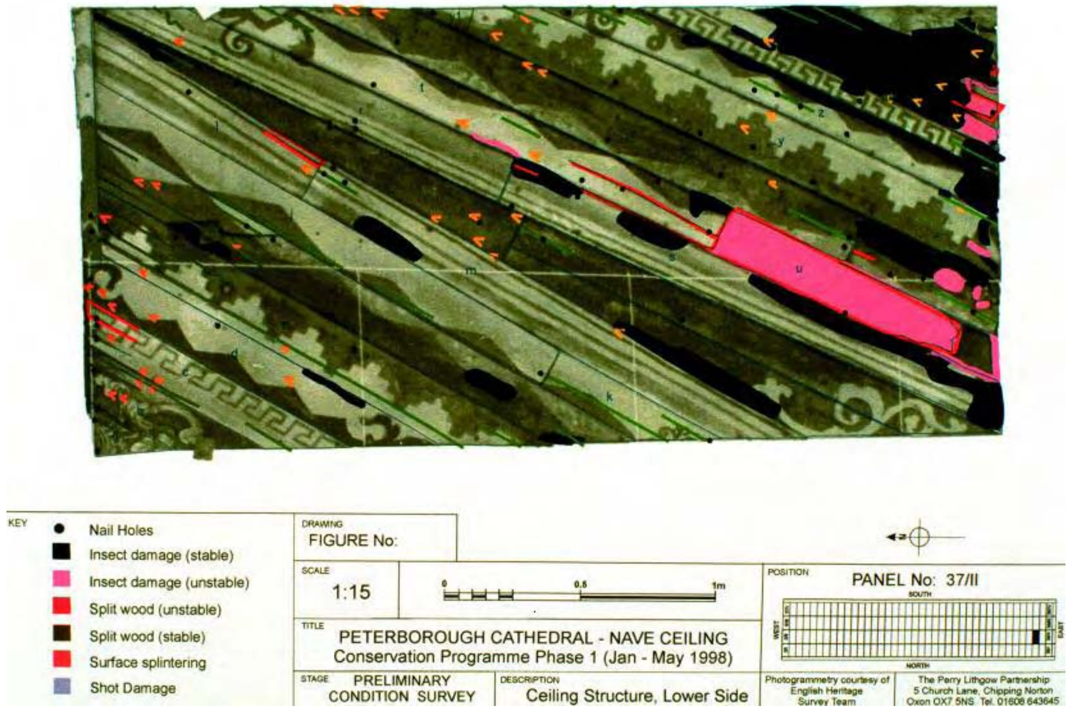


Fig 67
A plot of part of the orthophotograph of the Peterborough Cathedral ceiling overlaid with the photogrammetric line drawing and subsequently annotated by the conservators: using the orthophotograph and the line drawing, the conservators were able to work from an image of the ceiling as well as to outline the physical structures of the boards (produced by The Perry Lithgow Partnership).

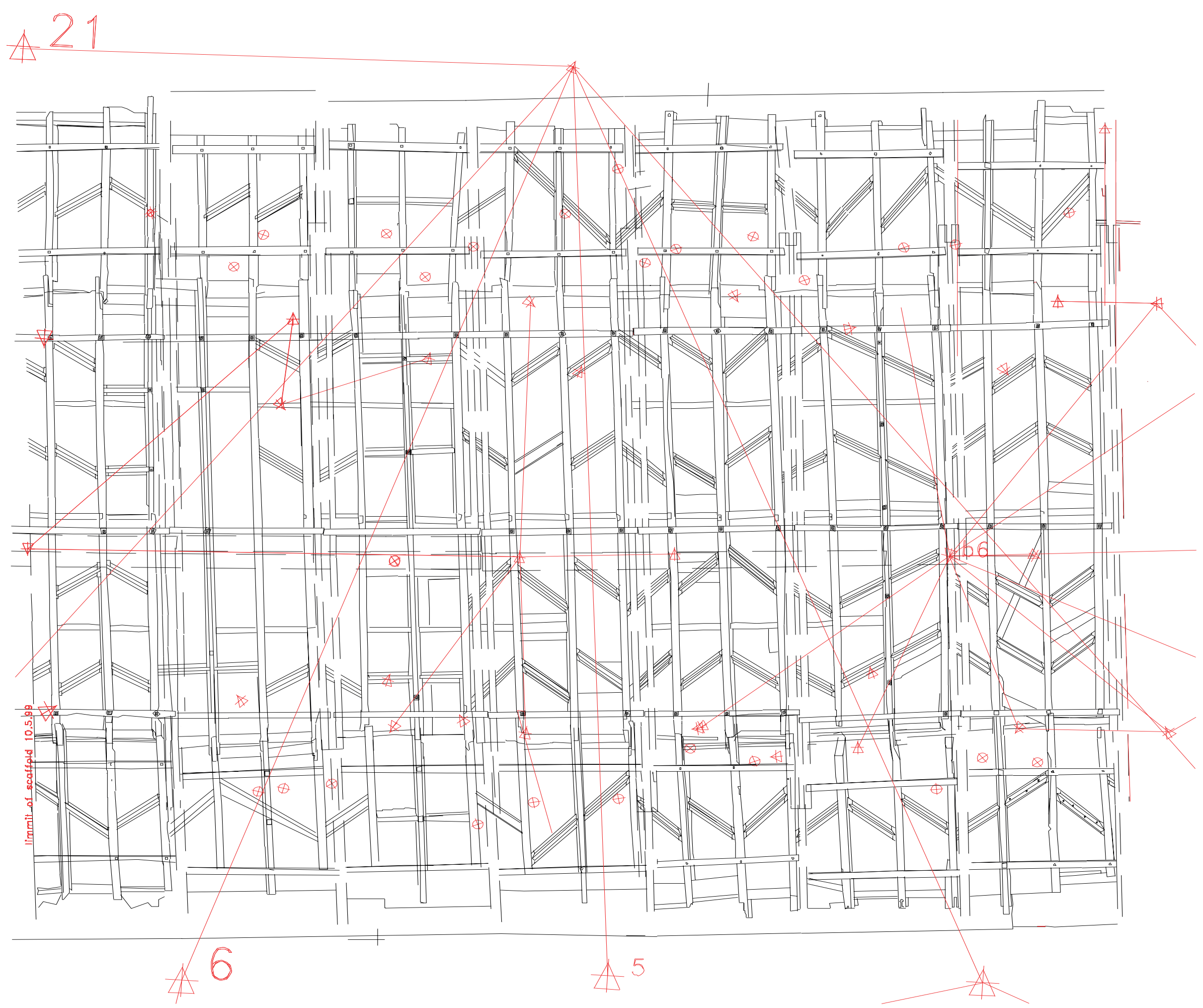


Fig 68
Part of the TST and hand survey of the dark side of the Peterborough Cathedral ceiling: the red lines indicate the complex control network that was required because the lines of sight were obscured by obstacles (compare Fig 63).

Every bolt, timber fixing, beam and other detail of the roof had to be recorded. The majority of the data was gathered using a reflectorless TST, which fed information directly into CAD. When the matt dark timber in the near-dark environment caused a weak return signal from the laser beam, detail points were measured using a prism on a detail pole. When detail was still inaccessible, hand measurements were taken and input directly into the CAD drawing.

Roof structures present particular problems to surveyors because of difficulties of access and limited space. Hand survey and reflectorless TST can help overcome these, but the lack of a line of sight meant that spur stations had to be set out from the existing traverse to capture obscured roof data (Fig 68). The roof drawing was completed in the office in CAD and individual elements were separated into groups to inform the understanding of the structure.

5.5.6 Appropriate techniques

The size of the ceiling and the inherent difficulties of access meant that an image-based survey method was the safest and most economical solution. The 3-D nature of the surface of the ceiling precluded the use of rectified photography, narrowing the choice to either photogrammetry or orthophotography. In the end the requirement for both the delineation of the boards and fixings and the depiction of the paintings meant that a combination of photogrammetry and orthophotography was required.

TST data combined with measured drawing have proved an economical survey technique where metric survey is required in areas that are confined, difficult to access and have limited lines of sight. As such, it was the only method considered for surveying the roof. The use of real-time CAD helped the surveyors in three ways: first, it was immediately apparent if spurious points had been recorded; second, having the recorded data as a CAD drawing gave the surveyor a visual reference of what had been surveyed and what data still needed to be captured; finally, measurements taken by hand could be entered directly into the CAD drawing, saving on time spent digitising in the office.

The need to survey the ceiling and its supporting roof structure required the adoption of several surveying techniques. The use of a single control system and CAD as the digital integration platform ensured that all the survey products could be combined and positioned in a local 3-D co-ordinate system. This made it possible to produce 2-D plots that combined photogrammetry (showing the roof structure) with orthophotography (showing the related ceiling structure), thus enabling the conservators to fix the painted boards from the flat side of the ceiling through to the roof structure above (Fig 69).

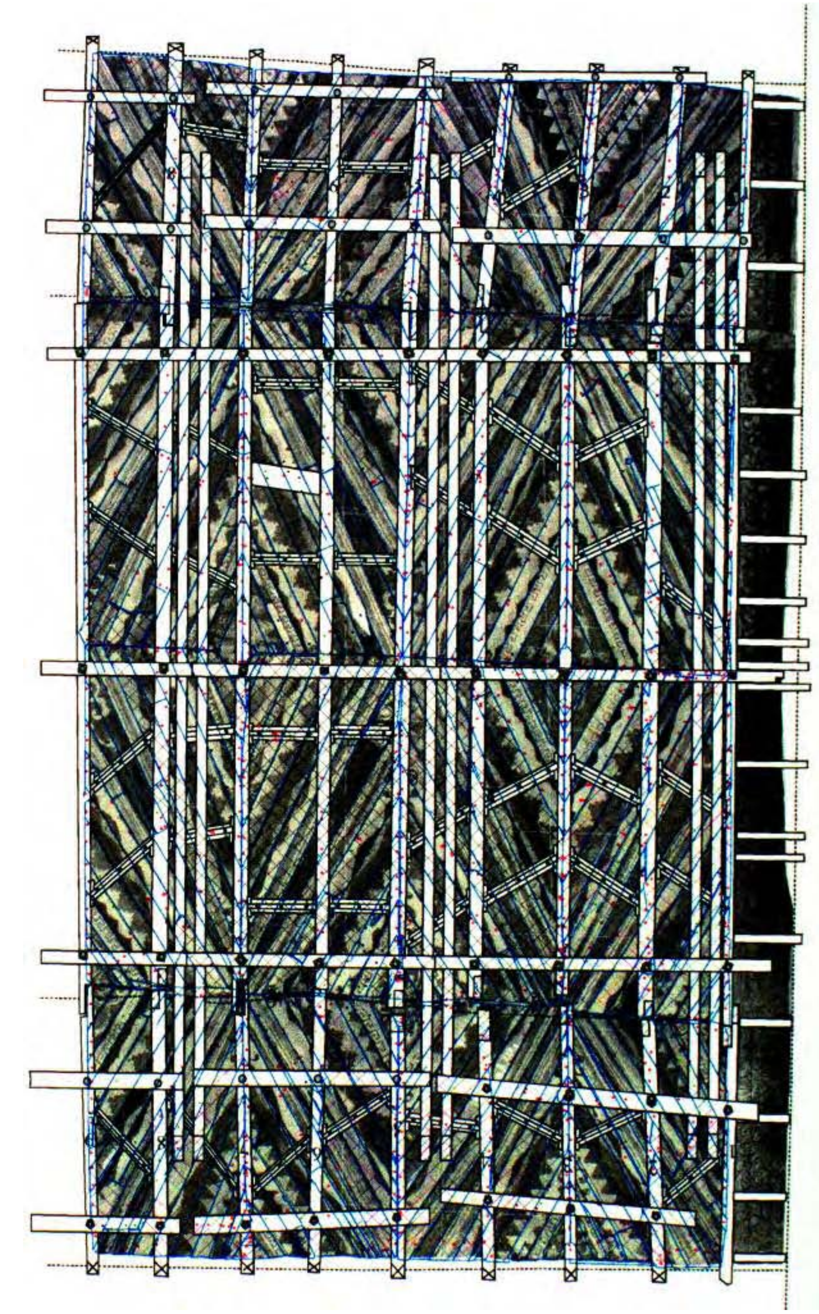


Fig 69
The Peterborough Cathedral ceiling superstructure was overlaid with the orthophotograph to make it possible for the conservators to match detail from the ceiling to the roof structure above (produced by The Perry Lithgow Partnership).

5.6 The 'Listening Ears': baseline condition recording with photogrammetry and laser scanning

Developed in secrecy over a 14-year period, sound mirrors were to form part of an experimental early warning system for detecting incoming aerial invasion. Built at various locations along the south and north-east coastlines of England they worked by collecting sound waves, which were reflected and focused onto a microphone sited at the mirror's focal point. As well as amplifying the sound waves, the microphone could be rotated by a trained 'listener' so as to pick up the maximum sound reflected off the mirror and thereby establish the direction of any in-coming aircraft.

The most famous examples of acoustic mirrors in England are at Denge on the Dungeness peninsula of the Kent coast, near to the village of Greatstone-on-Sea. Known as the 'Listening Ears', the site comprises three large concrete reflectors facing the English Channel – one long 200ft (61m) curved wall and two smaller 20ft (6.1m) and 30ft (9.1m) diameter dishes – built between 1928 and 1939 (Fig 70). Although the technology worked, the rapid and widespread adoption of radar in the 1930s promptly rendered it obsolete as an early warning system. The site closed in 1937 but its historical significance lives on as all three reflectors are now Scheduled Monuments. However, even this legislative protection has not prevented the gradual weathering and deterioration of these reinforced concrete structures through natural decay processes.

5.6.1. The survey requirement

Recent work at the site has concentrated on understanding the condition and stability of the structures, followed by addressing the most immediate conservation risks. In order to gauge the effectiveness of modern repairs and enable monitoring of the conditions of the structures over time, a baseline record was required by the project engineers and conservators.

When faced with the challenge of surveying what are now, due to the effects of weathering and natural decay, a series of irregular, concrete shapes, a combined approach using 'indirect' survey techniques was deemed appropriate. These included:

- photogrammetry to provide accurate line drawings of the basic structural outline, including any visible areas of degradation – through the acquisition of stereo photography this technique is able to provide mechanisms for selectively capturing both edge and surface detail, albeit at a much slower rate because of post-processing requirements;
- and laser scanning to record the concrete surfaces three dimensionally – this 'blanket' approach to mass data capture is more suited to rapidly recording surface information than to edge detail.

5.6.2 Photogrammetric survey

The photogrammetric survey was carried out during August 2005 by the English Heritage Photogrammetric Unit. A total of 156 stereo pairs were captured on site using the combination of a large format film-based metric camera, to capture the principal outline of the structure, and a high-resolution digital SLR camera to infill any remaining architectural detail. Three-dimensional survey control was observed using a TST to 213 'butterfly' style reference targets, placed directly on the concrete structures. To provide an appropriate accuracy of control data, despite the physical constraints of the site, both intersection and bearing/distance observation methods were employed. Computation of 3-D co-ordinates was carried out, including transformation of the locally derived values to the site co-ordinate system, as defined by the previous topographic survey of the site carried out back in 2003.

Scanning of the film-based photography, to provide the primary digital image files, was carried out through an external bureau using a photogrammetric scanner at 20-micron resolution. The line drawings, outlining both the principal architectural details and any visible areas of decay, were subsequently manually digitised on one of the unit's digital photogrammetric workstations running professional photo-grammetric software. The drawing data was formatted in CAD before producing output for the clients as scaled hard-copy plots on film and final deposition within the Historic Plans Room at the National Monuments Record Centre in Swindon.

5.6.3 Laser scanning

Following competitive tendering, APR Services Ltd were commissioned to carry out the laser scanning using a brief and specification developed by the English Heritage funded Heritage 3-D research project, aimed at developing professional guidance for laser scanning in archaeology and architecture. Site scanning was carried out over a two-day period in July 2005. Two different terrestrial laser scanners were used. Data was captured at two different native resolutions, deemed appropriate for recording the surfaces of the three concrete reflectors: a post-spacing of 5mm for the 20ft (6.1m) and 30ft (9.1m) dishes and a post-spacing of 10mm for the longer, 200ft (61m) wall.

To reduce the likelihood of voids appearing in the data, 3-D point clouds were observed from a number of different scanner locations. As two different scanners, each having their own specific data format, had been used the observed point cloud data was registered together using a combination of three different point cloud processing software packages so as to provide a series of meshed models output as in an industry-standard format for 3-D model data. As with the photogrammetry, these results were also referenced to the existing site co-ordinate system.

Fig 70
The acoustic mirror array at Greatstone-on-Sea, Kent.

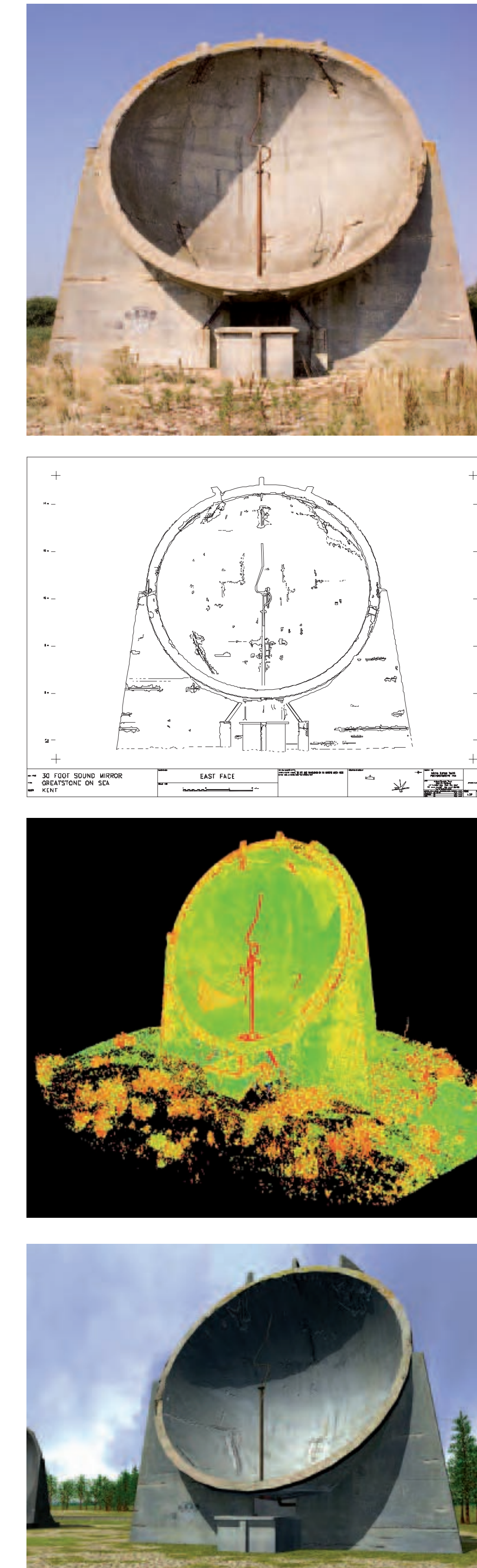


Fig 71
Top, one half of a stereo pair taken for the photogrammetric survey of the acoustic mirror array at Greatstone-on-Sea: the microphone site can be seen clearly; upper-middle, the wire frame derived from the stereo pairs presented in CAD; lower-middle, the point cloud data from the laser scanning – the post spacing was 10mm and the colours indicate variation in the reflectance of the surfaces recorded; bottom, rendered scene of the textured model derived from the laser scan point cloud and the site imagery. The model incorporated edge data from photogrammetry.

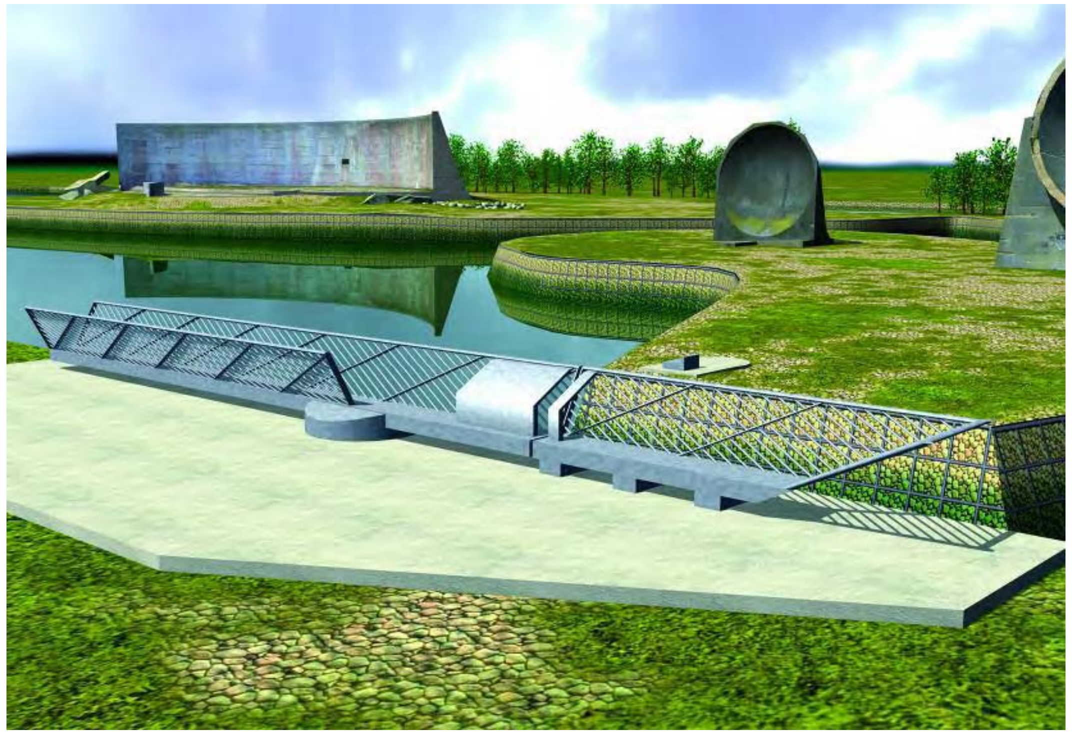


Fig 72
Rendered view of the Greatstone-on-Sea acoustic mirror array, with reconstructed detail added for site interpretation: the ground surface was captured concomitantly with the scans of the mirrors, enabling the disposition of the array and the adjacent topography to be recorded.

5.6.4 Conclusions and further work

As well as providing the accurate and detailed base-line record of each structure, (particularly the record of surface damage and deformation) this unique combination of line, point, mesh and image data (Fig 71) had additional uses. Given the limited public access to the site, the availability of a 3-D computer-generated model would undoubtedly prove useful in providing at least virtual access to the structures. With the short timescale and limited availability of additional project funding, this work was also carried out through an external contractor. Viriditas UK Ltd were commissioned in December 2005 to produce a detailed animated and textured 3-D model of the site based on the existing photogrammetric, laser scanning and topographic survey datasets (Fig 72). This work was principally carried out using professional modelling software, producing a 5Mb model file, excluding textures, along with an image processing package for manipulation of image textures. The resultant animations were output in both AVI and MOV formats in different resolutions to match the variable viewing requirements such as desk-top or web-based. Although such a model could theoretically have been generated using just one of the existing datasets and survey technologies, the combination and abundance of available 3-D data and digital imagery certainly accelerated the modelling process, as well as enhancing the accuracy, quality and flexibility of the final product.

5.7 The Northumberland and Durham Rock-art Project

Low-cost photogrammetry is suitable for routine heritage recording tasks at both large and small scales. Within English Heritage current examples include rock art and artefact recording as applied within the Northumberland & Durham Rock-Art project (NADRAP). Completed in July 2008, this project utilised volunteer groups to acquire large quantities of their own stereo-photography of a wide variety of carved stones and panels, alongside the other documentation data required by the project. In addition, a number of volunteers received training in the use of lower-cost photo-grammetry software, to enable them to process their own recording datasets. As two of the volunteers, Richard Stroud and Joe Gibson, explain:

"In addition to 3-D viewing and movement of carved rock panels, which in itself brings a greater reality than standard photography, the ability to remove distracting surface textures to better distinguish and assess artificiality and design components within markings is very useful. Previously undetected motif and design relationships have been revealed. Cup depth and shape can be better analysed and measured accurately on screen for comparison purposes. Digital Elevation Models (DEMs) of a reversed surface model can further clarify motif patterns and relationships. Essentially the photogrammetric process allows detailed desk based research on an accurate surface model without intrusion, removal or otherwise endangering easily damaged and irreparable panels. However, photogrammetry should not be used in isolation as an interpretive tool for rock art, and should be used in conjunction with field visits."

Another developing area of application is artefact recording, in which stereo-photography – taken with a calibrated, consumer-level digital camera from a range of up to 2m – can be acquired in conjunction with a simple set of scale bars. Although dependant upon a number of factors – including the resolution of the digital camera, the quality and angular coverage of the lens, the range over which photography is carried out and the surface texture of the object – this can still be used to provide not only a detailed metric photographic record of the object, but can also form the basis for:

- analytical interpretation of the detailing
- monitoring data, to enable an analysis of change over time
- presentation, in the form of a three-dimensional model in both textured and untextured forms.

More costly techniques, such as laser-scanning, will provide potentially higher resolutions and accuracies of 3-D data. However, the work to date has already demonstrated that a fast, cost-effective solution to wide-area recording can indeed be provided by a low-cost photogrammetric approach through an appropriate integration of technology and expertise.

Fig 73
3-D Digital Elevation Model (DEM) of rock art panel from Barningham Moor, Northumberland shown as (left to right) untextured, reversed and textured forms. Generated by Joe Gibson.

6 Conclusions

The balance between precision, cost and time when applying metric technologies to heritage documentation can be achieved by choosing an appropriate method and making sure project information requirements are understood by all from the start. The examples described in the case studies demonstrate how careful assessment of user information needs ensures a successful match of technique to project requirements. The effectiveness of a technique is dependant on its metric performance and its data selection characteristics. Direct techniques have the benefit of being highly selective, thematically specific and relatively low cost, but require detailed direction (either through specification or through the surveyor's experience) to be effective. Indirect techniques are efficient at wide-area or mass capture and the data can be used in a wide variety of ways, particularly for image-based methods where the image can act as effective documentation in its own right. Clarity over desired data outcomes is essential when working with indirect techniques, as they involve costly operations and method specific data types (for example point clouds or stereo pairs), which must be directed through a brief and specification to be effective.

6.1 Integration of techniques

In many cases a metric record of the built heritage requires a combination of techniques to be successful. The insight from site drawing combined with the robust precision of, for example, photogrammetry generates data with both architectural sensitivity and metric performance. Practitioners in heritage documentation must sustain a diverse range of skills, including site drawing and an understanding of significance and heritage value as well as metric technologies; without them we cannot conserve or manage our heritage places.

6.2 Base-level metric survey and ante-disaster records

Recording and monitoring the condition of heritage places is crucially important. Simple procedures can supply long-lasting and valuable information. The historic and current value of metric photography as a primary record should not be overlooked. The extraction of 3-D data may require the use of photogrammetric equipment and expertise, but its value as an ante-disaster record is without question. The acquisition of photogrammetric ante-disaster data sets has long-term benefits that cannot be overlooked when making risk assessments of historic fabric.

6.3 Archive and accessibility

The monitoring and re-evaluation stages of conservation will require re-examination of the metric record. This means metric survey must be archived in anticipation of future uses beyond the immediate. Digital data sets, despite all their advantages, are vulnerable to improper storage, system dependence and format compatibility. Therefore the brief for the survey needs to address not only immediate but also long-term data requirements to maximise its life and utility.

SUMMARY TABLE OF METRIC SURVEY TECHNIQUES

TECHNIQUE	Product		Application	Subject size	Constraints on use
INDIRECT TECHNIQUES: UNDIFFERENTIATED DATA AT CAPTURE					
REMOTE SENSING	3-D	Wide area landscape records.	Landscape monitoring, water content, mineral reflectance and vegetation health mapping etc.	1-1500Km^2	Dependant on wave band, will not resolve down to centimetric precision in most cases.
AIRBORNE LIDAR	3-D	Topographic mapping.	Landscape mapping and monitoring.	1-500Km^2	Post spacing at sub-metre resolution is costly.
AERIAL PHOTOGRAMMETRY	3-D				Co-ordinated flight plan and ground control.
TERRESTRIAL LASER SCANNING	3-D	Point clouds, surface models.	Building models and drawings.	5-500m^3	Point density must be matched to required information outcome. Congruent image capture needed.
CLOSE RANNGE PHOTOGRAMMETRY	3-D	Photo-maps, CAD drawings, ante-disaster records.	Architectural facade drawings, orthophotos, stereo pairs, surface models.	2-100m^3	Calibrated camera, optimised image capture, object area control, processing software and operator skill.
RECTIFIED PHOTOGRAPHY	2-D	Condition records.	Records of flat facades.	2-50m^2	Only single reference plane scalable.
ARTEFACT SCANNER	3-D	Point clouds, surface models.	Sculpture, relief carving etc.	1-5m^3	Controlled environment required.
DIRECT TECHNIQUES: DATA SELECTED AT CAPTURE					
GPS	3-D	Topographic mapping, point data.	Landscape surveys, inventory mapping, primary orientation to global co-ordinate system.	1-20Km^2	Open sky needed. Height precision can be a problem.
TOTAL STATION	3-D	CAD wire frames, point data.	Topographic mapping, building plans & sections. Precise control network measurement.	0.5-50m^3	Data organisation is needed by code, layer or GIS protocol, trained operators are required.
LEVELLING	2-D	Discrete point height monitoring.	Precise height points.	1-50m	Structural engineers: selected diagnostic points measured for movement monitoring.
DRAWING	2-D	Key detail records, explanatory diagrams.	Structural notes, architectural definition, excavation records.	0.25-5m^3	Selection of information based on subjective domain knowledge.

Table adapted from Santana Quintero, 2003

Appendix 1
Glossary

adjustment In the survey of control data, the method used to proportionally distribute observation and centring discrepancies acquired during the measurement procedure. Such techniques include the Bowditch, Transit and Least Squares Adjustment methods.

CAD Computer-aided design (CAD) is the use of computer technology to aid in the design and especially the drafting (technical drawing and engineering drawing) of a part or product, including entire buildings. It is both a visual (or drawing) and symbol-based method of communication, whose conventions are particular to a specific technical field.

cavetto From Latin cavare, 'to hollow': concave, quarter-round moulding sometimes employed in the place of the **cymatium** of a cornice.

chain and offset Procedure of setting out a local grid system of measurement consisting of a base line (the chain) and recording the distance along it to points that are then measured at right angles to it (the offset). Chain and offset measurements are usually booked in a tabulated manner to aid plotting.

co-ordinates A co-ordinate system defines points in space using values relative to the three axes: x, y and z (for a 2-D co-ordinate, the z value is omitted). In building survey, planar co-ordinates are used, but in topographic survey, representing the curved surface of the earth on a plane means a co-ordinate system with an appropriate **projection** is used.

cymatium The crowning member of a cornice, generally in the form of a double curved moulding (cyma, 'wave-like').

datum line A horizontal reference line used to control height. 'Datum' is also used to describe a fixed height point used as a common height reference on a site or building.

digitising The process of transcribing an object, image or document into a computer-readable form. In drawing production, digitising describes the tracing of features from either an existing drawing or a rectified photograph into CAD.

DTM/DEM A digital elevation model (DEM): a digital representation of surface topography or terrain. It is also widely known as a digital terrain model (DTM). A DEM can be represented as a raster image, point cloud data or as a triangulated irregular network (TIN). DEMs are commonly derived using remote sensing techniques; however, they can also be generated from land surveying data. DEMs are the most common basis for digitally produced relief maps. A DEM provides a so-called bare-earth model, showing only (in the case of topographic survey) the ground surface.

DXF DXF (Drawing Interchange Format, or Drawing Exchange Format) A CAD data file format developed by Autodesk® for enabling data interoperability between AutoCAD® and other programs.

EDM/REDM Electromagnetic Distance Measurement. The method used for measuring distances in a **TST**. When the EDM measured distance is combined with horizontal and vertical angles the position of a measured point is recorded in 3-D. EDM devices that work without a reflector are known as reflectorless, and the acronym REDM is widely used to describe them.

GPS (Global Positioning System) is the Global Navigation Satellite System (GNSS) in common use. It uses a constellation of satellites, which transmit microwave signals that enable GPS receivers to determine their location, speed, direction, and time by trilateration. Survey-grade GPS receivers are commonly used in topographic and control survey to provide 3-D points related to national mapping (Ordnance Survey National Grid in the UK).

isometric sketch An explanatory diagram in which the vertical axis is true, with horizontal axes displayed at 60° to each other.

laser plummet A vertical laser line projected from the base of a TST, used for centring over a specific point.

laser scanner Laser scanning is a method for the automated mass capture of 3-D points at fixed intervals. The scanner is used to create a 'point cloud' of the surface of the subject. These points can be used to extrapolate the shape of the subject. If colour or reflectance intensity information is also collected at each point, then this can also be mapped.

level line Use of string, chalk or a laser to define a horizontal line from which vertical measurements can be taken (*see also* **datum line**).

model parity A term used to describe the equivalence of a 3-D model to its corresponding subject. The parity (equivalence) of the model will depend upon the level of detail recorded by a survey, defined by the accuracy, precision and density of the points recorded.

mutule One of a series of projecting inclined blocks of a Doric cornice: the sloping, block-like brackets beneath the cornice corona.

plumb line Use of string, chalk or a laser to define a vertical line from which horizontal measurements can be taken, often used to control measured drawing surveys (*see also* **datum line** *and* **level line**).

point cloud *see* **laser scanner**

projection Any method used to represent a 3-D surface on a plane. The term 'projection' here refers to any function used to transpose 'real world' geometry onto a plane. Projections are formalised in architecture as plan, section and elevation: a plan is a horizontal projection and sections and elevations are vertical.

station A fixed point with co-ordinate values determined to a high order of precision used for instrument occupation during survey; a point within a control network with its adjusted location determined by distance and bearing measurements to adjacent stations (*see also* **adjustment** *and* **witness diagram**).

topographic survey The generation of 3-D controlled measurements of natural and man-made features in a landscape. The results are usually presented as plans or maps, characterised by large-scale detail and quantitative representation of relief (usually using contour lines).

tribrach An interchangeable, adjustable base plate for centring and levelling survey equipment that is fixed to the tripod stage plate.

TST total station theodolite

wire frame A wire frame model is a representation of the edges of an object. The points, lines and curves measured during survey form a skeletal framework in a CAD drawing defining the edges of the object in 3-D, but not its surfaces. The data generated by **TST** survey or the vector output from photogrammetric plotting are examples of such products.

witness diagram A diagram that describes the position of control stations generated during a survey to aid the location and re-occupation of stations. Such a diagram includes the 3-D co-ordinate values of the station, a written description of the point or marker used and at least three measurements taken to fixed details.

Appendix 2
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Appendix 3
Information sources

Ancient Monuments Society
St Ann's Vestry Hall
2 Church Entry
London EC4V 5HB
020 7236 3934
www.ancientmonumentssociety.org.uk
AMS publishes lists of historic buildings under threat of demolition, details about their casework activities and a list of related links.

Archaeology Data Service (ADS)
Department of Archaeology
University of York
King's Manor
York YO1 7EP
01904 433 954
http://ads.ahds.ac.uk
Provides guidance on the preservation and migration of digital data in the form of 'Good Practice' guides.

The Association of Archaeological Illustrators & Surveyors (AAIS)
SHES, University of Reading
Whiteknights
PO Box 227
Reading RG6 6AB
info@aais.org.uk
www.aais.org.uk
Publishes a tri-annual journal, available online, as well as careers advice and membership information.

Association of Local Government Archaeological Officers (ALGAO)
C/O Planning Department
Essex Country Council
County Hall
Chelmsford
Essex CM1 1QH
www.algao.org.uk
A forum that provides a series of publications based on the work of the ALGAO, and describes the role of archaeology in local government.

CADW
Welsh Assembly Government
Plas Carew, Unit 5/7 Cefn Coed
Parc Nantgarw
Cardiff CF15 7QQ
01443 33 6000
www.cadw.wales.gov.uk
CADW are the historic environment department of the Welsh Assembly Government. The website offers information on the activities of CADW, their properties, publications and learning resources as well as details on legislation and advice for home owners.

CIPA
(the ICOMOS/ISPRS Committee for Documentation of Cultural Heritage)
http://cipa.icomos.org
Contains information on the working groups, publications and events organised by CIPA relating to their work with cultural heritage professionals.

The Construction History Society
The Secretary
Construction History Society
C/O Library and Information Services Manager
The Chartered Institute of Building
Englemere, Kings Ride, Ascot
Berkshire SL5 7TB
www.constructionhistory.co.uk/

English Heritage
1 Waterhouse Square
138–142 Holborn
London EC1N 2ST
www.english-heritage.org.uk
www.english-heritage.org.uk/server/show/nav.1681
Provides information on the research and conservation work conducted by English Heritage as well as information relating to events, properties and learning resources.

Garden History Society
70 Cowcross Street
London EC1M 6EJ
020 7608 2409
www.gardenhistorysociety.org/
Information relating to the issues affecting historic parks, gardens and landscapes that includes links to the GHS library, relevant organisations, and a series of publications.

Getty Conservation Institute
The Getty Conservation Institute
1200 Getty Center Drive, Suite 700
Los Angeles, CA 90049-1684
www.getty.edu/conservation/institute/index.html
Provides advice on conservation techniques and principles and details public lectures, publications and field projects conducted by the institute.

Heritage3-D
www.heritage3-D.org
Offers advice on best practice in laser scanning techniques by providing a forum for discussion, a series of case studies and downloads relating to a variety of applications.

Heritage information
www.heritageinformation.org.uk
An independent resource providing conservation information to members and specialist applicants.

Historic American Buildings Survey
www.cr.nps.gov/habshaer
The US federal government's documentation program. The website provides information on employment, online architectural and engineering collections and HABS projects.

Historic Scotland
Longmore House
Salisbury Place
Edinburgh EH9 1SH
0131 668 8600
www.historic-scotland.gov.uk/
This website offers information and technical guides regarding conservation of the historic environment, and information relating to the properties in the care of Historic Scotland. Learning resources and information on policies are also available.

The Institute of Conservation (ICON)
109 The Chandlery
50 Westminster Bridge Road
London SE1 7QY
020 7721 8721
www.icon.org.uk
Conservation advice, news, awards, discussion and publications.

Institute of Historic Building Conservation
3 Stafford Road
Tunbridge Wells
Kent TN2 4QZ
01483 252000
www.ihbc.org.uk
A UK-wide professional body that provides building conservation guidance, a discussion forum and links to architectural institutions.

International Council on Monuments and Sites (ICOMOS)
UK office:
10 Barley Mow Passage
London W4 4PH
020 8994 6477
www.icomos.org
Details the charters adopted by the ICOMOS committees, a calendar of the associated events, and a link to the documentation centre maintained by the council.

International Society for Photogrammetry and Remote Sensing (ISPRS)
www.isprs.org/
A collection of documents and publications produced by the ISPRS, as well as information about the society, commissions and associated events.

National Trust
Heelis
Kemble Drive
Swindon SN2 2NA
01793 817400

36 Queen Anne's Gate
London SW1H 9AS
0870 609 5380
www.nationaltrust.org.uk
Information on the conservation, heritage and learning schemes offered by the National Trust, and details about their properties and events.

Remote Sensing and Photogrammetry Society (RSPSoc)
The Remote Sensing and Photogrammetry Society
C/O Department of Geography
The University of Nottingham
University Park
Nottingham NG7 2RD
0115 951 5435
www.rspsoc.org/
Details about the activities of RSPSoc, including events, publications and resources.

The Royal Commission on the Ancient and Historical Monuments of Scotland (RCAHMS)
RCAHMS
John Sinclair House
16 Bernard Terrace
Edinburgh EH8 9NX
0131 662 1456
www.rcahms.gov.uk/
Provides a description of the survey methods used by RCAHMS as well as a series of searchable databases, information concerning outreach programs and collections information.

The Royal Commission on the Ancient and Historical Monuments of Wales (RCAHMW)
RCAHMW
Plas Crug,
Aberystwyth SY23 1NJ
01970 621200
www.rcahmw.gov.uk

Royal Institute of British Architects (RIBA)
66 Portland Place
London W1B 1AD
020 7580 5533
www.architecture.com
General information about architectural resources, including careers information, links to reference collections and practicing architects, debating forums and news articles.

RIBA Library
www.architecture.com/go/Architecture/Reference/Library_898.html
A searchable online catalogue of books, drawings and RIBA periodicals. Also includes a biographical database of architects.

Royal Institution of Chartered Surveyors (RICS)
RICS Contact Centre
Surveyor Court
Westwood Way
Coventry CV4 8JE
0870 333 1600
www.rics.org
This website contains a wealth of information on environmental, property, management and training issues relating to surveyors, as well as guidelines.

RICS Geomatics Home Page
www.rics.org/Environmentalandlandconsultancy/Geomatics/
A specialised site dedicated to the Geomatic survey skill-set, including photogrammetry and remote sensing.

Society of Architectural Historians of Great Britain
Pixham Mill
Pixham Lane
Dorking
Surrey RH14 1PQ
www.sahgb.org.uk
Provides a list of publications available from the society, a skills directory and register of postgraduate research in architectural history.

Society for the Protection of Ancient Buildings (SPAB)
37 Spital Square
London E1 6DY
020 7377 1644
www.spab.org.uk
A detailed list of educational courses run by the society and a publications and advice section detailing specific resources.

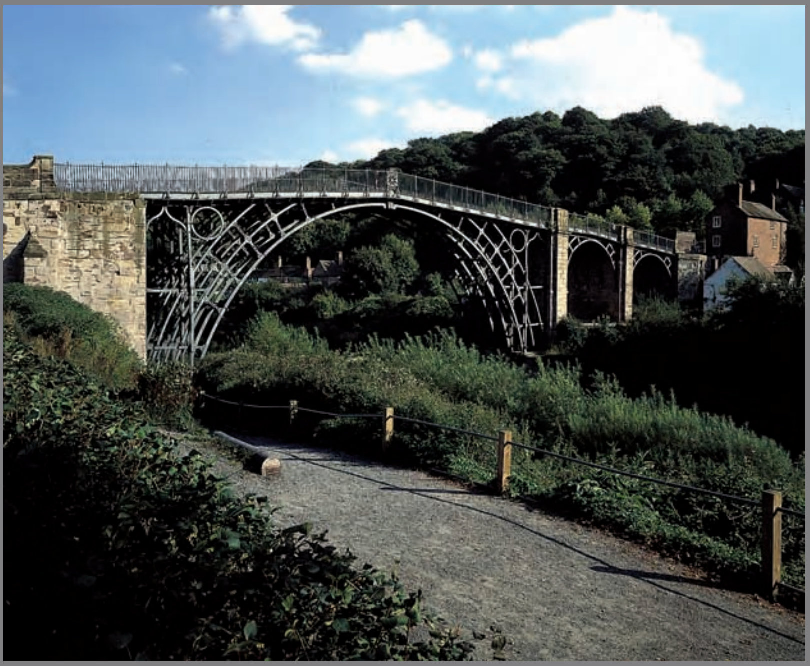
The Survey Association
The Survey Association
Marine House
Thorpe Lea Road
Egham
Surrey TW20 8BF
01784 223 760
www.tsa-uk.org.uk
A useful site for external contractors; a full list of members is available, as well as forthcoming events information and links to relevant institutions and organisations.

World Heritage Centre
http://whc.unesco.org
The World Heritage Centre is a UNESCO initiative, and provides links to conservation reports, case studies, operational guidelines and committee details.

Index

Figures in **bold** refer to illustrations, figures in *italic* refer to tables.

The publication of English Heritage's *Conservation Principles: Policies and Guidance for the Sustainable Management of the Historic Environment* (2008) has placed documenting and learning from decisions as a core principle, with accessible records recognised as essential to the conservation process. These principles outline the need for adequate records in managing change to significant places. *Measured and Drawn* sets out to show how, through working closely with historians, conservators and archaeologists, such records are achieved by metric survey.



The metric survey of our historic environment is a crucial part of our understanding. Mapping the historic estate means that it can be conserved, managed and enjoyed. This book gives an introduction to the techniques currently available to conservation professionals and building archaeologists.

Measured and Drawn examines control, detail and procurement, and concludes with case studies of metric survey projects undertaken on historic buildings and structures ranging from Battle Abbey Courthouse to the nave ceiling at Peterborough Cathedral. It is prepared in sequence with *Where on Earth are We? The Global Positioning System (GPS) in archaeological field survey* (2003), *Understanding Historic Buildings: a guide to good recording practice* (2006) and *3-D Laser Scanning for Heritage: advice and guidance to users on laser scanning in archaeology and architecture* (2007), as part of an ongoing series of English Heritage technical guides on heritage documentation.

Cover illustration: Rendered view of the CAD model of the Ironbridge, Shropshire. The CAD model was a product of a programme of historical and structural analysis concomitant with conservation works.
Back cover: The Iron Bridge at Coalbrookdale.

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