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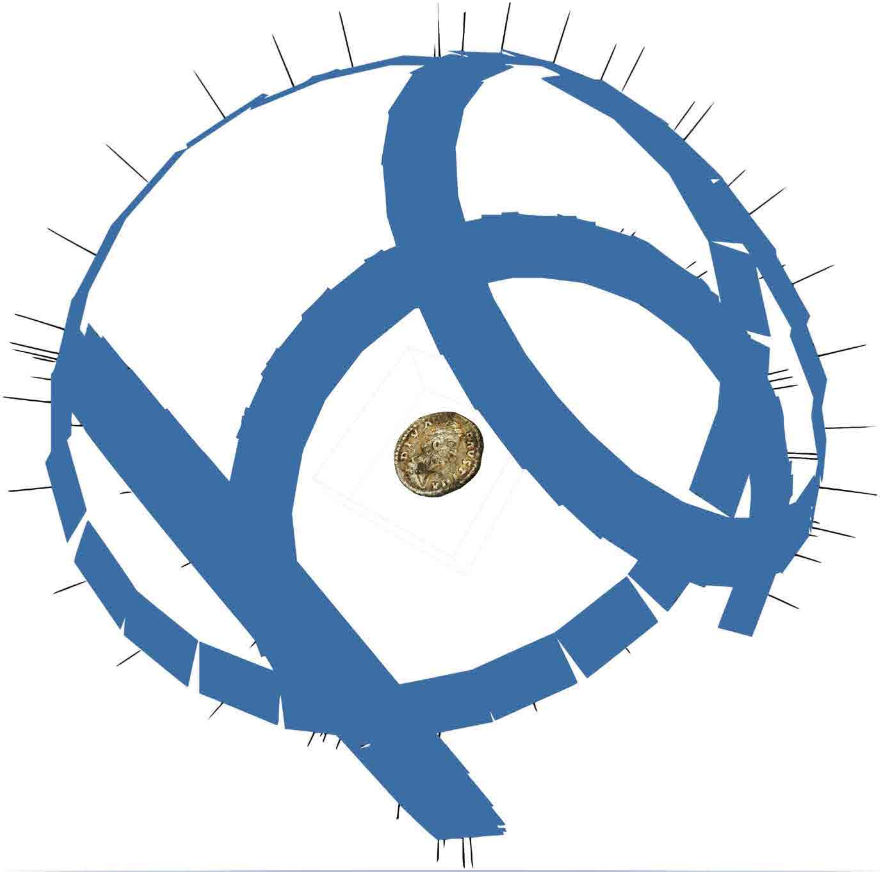

DIGITAL TECHNIQUES FOR DOCUMENTING AND PRESERVING CULTURAL HERITAGE

Edited by **ANNA BENTKOWSKA-KAFEL** and **LINDSAY MacDONALD**

Collection Development, Cultural Heritage, and Digital Humanities

ARC HUMANITIES PRESS

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LIST OF ACRONYMS AND ABBREVIATIONS

3D	Three-dimensional
4D	Four-dimensional
AAT	*Art & Architecture Thesaurus® Online*, Getty Vocabulary Program, J. Paul Getty Trust, USA
ACM	Association for Computing Machinery, USA
AHRC	Arts and Humanities Research Council, UK
AOTF	Acousto-Optical Tunable Filter
AR	Augmented Reality
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing Materials
ATR	Attenuated Total Reflectance
BHRT	Bosnia Herzegovina Radio Television
BIM	Building Information Modelling
CAD	Computer-Aided Design
CBIR	Content-based Image Retrieval
CCD	Charge-Coupled Device
CD-ROM	Compact Disc-Read Only Memory
CH	Cultural Heritage
CIDOC	International Committee for Documentation (within ICOM)
CIE	Commission Internationale de l'Éclairage
CIPA	Comité International de Photogrammétrie Architecturale (within ICOMOS)
CMM	Coordinate Measurement Machine
CMOS	Complementary Metal-Oxide-Semiconductor
CMS	Collection Management System
COSCH	Colour and Space in Cultural Heritage, COST Action TD1205, 2012–16
COST	European Cooperation in Science and Technology
CPU	Central Processing Unit
CRISATEL	Conservation Restoration Innovation Systems for image capture and digital Archiving to enhance Training, Education and lifelong Learning (EU FP5-IST-1999-20163 project 2001–4)
CRM	Conceptual Reference Model
CT	Computed Tomography
DEM	Digital Elevation Map

DOI	Digital Object Identifier
DSLR	Digital Single Lens Reflex (camera)
ECCO	European Confederation of Conservator-Restorers' Organisations
ECI	Early Career Investigator
EDM	Electronic Distance Measurement/Meter
EDS	Energy Dispersive Spectroscopy
EDX	Energy Dispersive X-ray Spectroscopy
EPSRC	Engineering and Physical Sciences Research Council, UK
ERA	European Research Area
ESR	Early Stage Researcher
EU	European Union
FADGI	Federal Agencies Digitization Guidelines Initiative, USA
FTIR	Fourier Transformed Infrared Spectroscopy
FWHM	Full Width Half Maximum
GFC	Goodness-of-Fit Coefficient
GIS	Geographic Information System
GPS	Global Positioning System
GSD	Ground Sampling Distance
HBIM	Heritage Building Information Modelling
HD	High Definition
H-RTI	Highlight Reflectance Transformation Imaging
HSI	Hyperspectral Imaging
HTML	Hypertext Markup Language
ICCROM	International Centre for the Study of the Preservation and Restoration of Cultural Property
ICOM	International Council of Museums
ICOM-CC	International Council of Museums-Committee for Conservation
ICOMOS	International Council on Monuments and Sites
ICP	Iterative Closest Point (algorithm)
ICT	Information Communication Technology
IEEE	Institute of Electrical and Electronics Engineers, USA
IET	The Institution of Engineering and Technology, UK
IFAC-CNR	Istituto di Fisica Applicata Nello Carrara, The Nello Carrara Institute of Applied Physics in Sesto Fiorentino, Italy, part of the National Research Council (CNR)

IS	Imaging Spectroscopy
ISO	International Organization for Standardization
ISPRS	International Society for Photogrammetry and Remote Sensing
IVE	Interactive Virtual Environment
JCGM	Joint Committee for Guides in Metrology
Laser	Light Amplification by Stimulated Emission of Radiation
LCTF	Liquid Crystal Tunable Filter
LED	Light-Emitting Diode
LIBS	Laser-Induced Breakdown Spectroscopy
LIDAR	Light Detection and Ranging (remote sensing)
LS	Laser Scanning
MARC	Methodology for Art Reproduction in Colour (EU FP3-ESPRIT 6937 project 1992–95)
MoU	Memorandum of Understanding
MSI	Multispectral Imaging
MVS	Multiple View Stereovision
n/a	not applicable
NEH	National Endowment for the Humanities, USA
NIR	Near Infrared
OBJ	Computer file format for 3D geometry definition
OIML	International Organization of Legal Metrology
OWL	Web Ontology Language
PEG	Polyethylene Glycol
PGP	Prism-Grating-Prism
PLY	Polygon File (computer file 3D format)
PS	Photometric Stereo
PTFE	Polytetrafluoroethylene
PTM	Polynomial Texture Mapping
PXRF	Portable X-ray Fluorescence (Spectroscopy)
R&D	Research and Development
RDFa	Resource Description Framework in Attributes
RGB	Red Green Blue
RIC	*The Roman Imperial Coinage* (see Mattingly and Sydenham 1923)
RMSE	Root-Mean-Square Error
ROV	Remotely Operated Vehicle

RRT	Round Robin Test
RS	Recommender System
RTI	Reflectance Transformation Imaging
SEM	Scanning Electron Microscopy
SfM	Structure from Motion
SIVT	Spatial Image analysis and Viewing Tool
SLI	Structured Light Imaging
SLR	Single Lens Reflex (camera)
SLS	Structured Light Scanning
SOP	Standard Operating Procedure
SPD	Spectral Power Distribution
SPIE	Society of Photographic Instrumentation Engineers
STSM	Short-Term Scientific Mission
SWIR	Short-Wave Infrared
TIN	Triangulated Irregular Network
TLS	Terrestrial Laser Scanner
TOF	Time of Flight
UAV	Unmanned Aerial Vehicle
UNESCO	United Nations Educational, Scientific and Cultural Organization
URL	Uniform Resource Locator
USB	Universal Serial Bus
UV	Ultraviolet
VASARI	Visual Art System for Archiving and Retrieval of Images (EU FP2-ESPRIT 2 project 1989–92)
VDI/VDE	Verein Deutscher Ingenieure / Verband der Elektrotechnik Elektronik Informationstechnik
Vis	Visible
VNIR	Visible and Near Infrared
VR	Virtual Reality
VRML	Virtual Reality Modelling Language
WG	Working Group
XML	eXtensible Markup Language
XRF	X-ray Fluorescence Spectroscopy

FOREWORD

COSCH stands for Colour and Space in Cultural Heritage and represents four years of networking activities of scientists and researchers from other disciplines from twenty-eight European countries. They share a dedication to improving the understanding of optical measurement techniques, applied to various tasks in documentation of material cultural heritage. The COSCH network benefited from the support and funding of the European Cooperation in Science and Technology, commonly known as COST. COST was founded in 1971 as an intergovernmental framework for cooperation in science and technology and is one of the oldest European bodies funding networking in these areas. Cooperation is implemented through the so-called Actions, such as COSCH. A COST Action provides a platform for dialogue and exchange of interdisciplinary knowledge amongst researchers from different academic disciplines, as well as industry and commercial research laboratories.

COST Actions have a funding period of four years. The funding covers networking activities, mainly the cost of organizing and travelling to meetings, conferences, and workshops. Financial support is also available for research exchange visits (so-called Short-term Scientific Missions, or STSMs), training schools, publications, and other dissemination activities. Personnel costs cannot be funded, which distinguishes COST Actions from research projects supported through the framework programmes of the European Union, such as Horizon 2020 and the earlier 7th Framework Programme (FP7) for Research and Technological Development. The networking character of COST Actions is paramount. Despite the lack of research funding, COST Actions have nonetheless a clear scientific focus that guides work conducted in the course of all activities. COST takes a bottom-up approach to the selection of proposals for funding: any kind of scientific objectives held by an international group of researchers may compete for support, if it fits within the COST implementation rules. When accepted, a proposal is transformed into a Memorandum of Understanding (MoU) and is signed by all participating countries. This document defines the objectives, programme of work, its milestones and measures to be implemented by the Action. The summary of the COSCH MoU (2012, p. 3) reads:

> True, precise and complete documentation of artefacts is essential for conservation and preservation of our cultural heritage (CH). By ensuring access to the best possible documentation of artefacts we are contributing to the enhanced understanding of material CH and help its long-term preservation. We are all responsible for ensuring that this heritage is

> passed on to future generations. Documentation of CH involves researchers, scientists and professionals from multiple disciplines and industries. There is a need to promote research, development and application of non-contact optical measurement techniques (spectral and spatial) adapted to the needs of heritage documentation on a concerted European level, in order to protect, preserve, analyse, understand, model, virtually reproduce, document and publish important CH in Europe and beyond. Research in this field typically relies on nationally-funded projects with little interaction between stakeholders. This Action will provide a stimulating framework for articulating and clarifying problems, sharing solutions and skills, standardising methodologies and protocols, encouraging a common understanding, widening applications and dissemination. The Action will foster open standards for state-of-the-art documentation of CH. It will simplify the usage of high-resolution optical techniques in CH and define good practice and stimulate research.

COSCH represents four years of intense interdisciplinary work, to the benefit of our common cultural heritage, aimed at optimizing its documentation through a better understanding of technology, and its dependencies on the questions and requirements of specific applications. Exemplary case studies in applied technology, in accordance with identified guiding research questions, are the main subject of this book. They represent the practical work which has been conducted in order to meet the COSCH objectives.

Frank Boochs
COSCH Chairman

INTRODUCTION

ANNA BENTKOWSKA-KAFEL

This book presents some of the outcomes of interdisciplinary research and debates conducted by the participants in the international network, Colour and Space in Cultural Heritage (COSCH) between 2012 and 2016. The book adds to a large body of literature on the applications of digital technologies to the study and preservation of cultural heritage. So why was another book on the subject needed? In this introduction the rationale for the book, its scope, and methodology are explained.

Cultural Heritage

After a certain period of time, human cultural activities and their products acquire the status of cultural heritage. The International Council on Monuments and Sites (ICOMOS 2002, 21) defines cultural heritage broadly as "an expression of the ways of living developed by a community and passed on from generation to generation." Some standard definitions of cultural heritage, both tangible and intangible, in the context of 3D documentation, have been collated by the consortium, 3D-COFORM (Arnold et al. 2009, 16–19).[1]

No single book can cover the variety and richness of cultural heritage, or the methods of its documentation. The limitations are inevitable. The COSCH network limited its interests to material objects of the cultural heritage of Europe, some of which are covered in this book. The objects and sites come from different periods and bear witness to different cultures. They vary in scale and materials, significance and value. They include an ancient Greek vase, the Karabournaki kantharos (chapter 2); Roman silver coins, the denarii of Faustina the Elder (chapter 3); painted wall decoration of the medieval French château of Germolles (chapter 4); a fortress overlooking Sarajevo, steeped in the multicultural, turbulent history of Bosnia (chapter 5); a medieval wooden shipwreck, known as a cog, lifted from a river bed in Germany (chapter 7); and a variety of historic objects housed by the National Museum of Romanian History, Bucharest, including icons, illuminated manuscripts, and pottery (chapter 6). Other works of world art and architecture, as significant

1 Major research projects in this area are often better known through their acronyms than full names, some of which tend to be very long and when used in a sentence distract from the main argument. The acronyms used by the authors can be found, spelled out, in Selected Bibliography, p. 277, see also Acronyms and Abbreviations, p. xxvii.

as the ancient, rock-cut statues of Buddha in the Bamiyan Valley in Afghanistan, demolished by the Taliban in 2001, are mentioned in the second part of the book. This small selection is representative of other art, crafts, and architecture, in various states of preservation and restoration that can be found *in situ* or housed in museums.

COSCH was established to enhance and promote specialist applications of optical technologies to the spatial and spectral recording of material cultural heritage. The research processes and some digital outputs of such applications (both digitally born and digitized) represent cultural heritage in its own right and require effective digital preservation. The significance of digital heritage has been recognized by UNESCO (2003b). Museum collections, archives, and other heritage organizations, motivated to some extent by a growing public demand, are under pressure to digitize their holdings. Yet we need to remember that only a small proportion of world cultural heritage has been digitized. The automation of digitization is seen as a way forward (Karaszewski et al. 2014), but not without concerns over the quality achieved by fast and uniform machine processes applied to unique objects. Issues of long-term digital preservation are also common. As noted in chapter 7, the long-term maintenance and access to digital tools and resources remain problematic, constituting a major barrier to the wider adoption of digital research methodologies. Only a fraction of digital assets thus created since the 1980s continue to be wanted, accessible, and usable. Technical solutions to digital obsolescence are available, but there are other reasons for neglect of electronic resources created in the past. The 3D computer model of the Old Minster in Winchester, created by archaeologists of the site in collaboration with IBM Research UK in the mid-1980s (3DVisA, 2006) exemplifies how research methods and outcomes that were cutting-edge in their day have fallen behind current expectations of digital, interdisciplinary scholarship. The model nonetheless represents an important step in the history of digital scholarly collaborations and is worthy of inclusion in a museum of computing or a museum of virtual archaeology.

Colour

Those new to the name, Colour and Space in Cultural Heritage, will read into this phrase a preconceived understanding of colour and space. Both concepts are so familiar to the experience of cultural heritage and life in general, that an explanation may seem redundant. An understanding of the concepts will, however, differ from one reader to another, so much so that a common understanding must not be assumed.

Colour "is the child of light, the source of all life on earth" (Delamare and Guineau 2000, 13). Johann Wolfgang von Goethe (1810) believed that colour is a level of darkness. He disputed Isaac Newton's (1704) discovery of the spectrum—the rainbow of colours of visible light after it passed through a prism. Newton's drawing of what he termed the "crucial experiment" (Newton 2010) shows sunlight refracted into five constituent colours, as he could not quite decide upon their number. The diagram, in black ink on paper, is a lasting, graphic record of his discovery process. Although since dismissed by modern science, Goethe's intuitive and poetic ideas about science and psychology of colour have continued to influence cultural theories. Since the earliest known cave paintings, artists have had a very special relationship with colour, not only physical, even tactile, but primarily spiritual. Our visual response to colour is emotional.

Colour in the arts is associated with pigments used to make paint, and dyes to colour textiles, but also with musical analogies to tint, tone, and hue, and further to chromatic harmony. From the quantifiable measures of the physical properties of colour to the significance of colour as an indicator of race, the range of possible references to cultural heritage is endless. The power of colour is forcefully expressed in the painting *Potent Fields* (2002, British Museum, London) by the South-African artist, Karel Nel, in which two planes, one in white ochre and the other in dark red ochre, refer to the separateness (apartheid) of colour. This powerful reading is only apparent to the informed beholder. Artwork detached from its message and context risks being meaningless. One must recognize that no documentation of a material object is ever complete unless its historical, social and phenomenological, spiritual and symbolic aspects are also studied. Conservation and heritage science are also capable of bringing back some of the lost meaning. Discolouration of paint or varnish over time, for example, influences the perceived meaning of art, as the well-known painting by Rembrandt van Rijn, showing a militia group portrait in daylight, continues to be popularly called *Night Watch* (1642, Rijksmuseum, Amsterdam).

Colour and Space in Cultural Heritage was led by the Technical University of Applied Science in Mainz, the COSCH Action grant holder. COSCH participants met in many different places in Europe, also in Mainz, which is famous for being the birthplace of Johannes Gutenberg and an apt place to deliberate the progress in documentation and reproduction technologies. For those who love the exuberance of colour in art, St. Stephen's church in Mainz is a perfect destination. The stained-glass windows there were designed by the ninety-year-old Marc Chagall, who was, according to Picasso, the only painter (after Matisse) to understand colour. "When Matisse dies," Picasso is known to have said, "Chagall will be the only painter left who understands what colour really is."[2] The colour scheme is

2 Françoise Gilot and Carlton Lake, *Life with Picasso* (London: Virago, 1990), 265.

predominantly cobalt blue with vivid accents of red, black, and yellow, ever changing in the daylight. The glowing effect is spiritual, even heavenly for some. What influences the artist's choice of paint or draws the viewer to particular colours may be investigated from aesthetic, psychological and many other perspectives. While recognizing this, the COSCH network's research into this area, however, has primarily been scientific with a focus on the capture of the intensity of radiation reflected at each wavelength from each point on a coloured surface (see, for example, Casini et al. 2015; Nascimento et al. 2017).

When in the early 2000s the Corpus Vitrearum Medii Aevi embarked upon digitization of medieval stained-glass that have survived in Great Britain (www.cvma.ac.uk), it surprised everyone how well the luminous effect of digital images displayed on a monitor screen, then glass, simulated the viewing of actual stained-glass windows. This was a visible, positive point of digitization. The process had many critics. Digitization in those days mainly involved scanning slides (particularly in teaching collections), negatives, and photographic prints. The laboriousness and exorbitantly high costs were of concern. A blank CD-ROM, then a popular portable data storage medium, retailed at approximately £12/$18 each in 1998, and could hold no more than 650MB of read-only data. Various major technical issues involved in the processing and storing of digital data, their presentation and dissemination have since been resolved. Importantly, the direct digitization of the artefact, without the intermediary of a photographic surrogate, is now not only possible, but commonplace. Although amateur photographers rarely control the quality of the photographs they take, tending to rely on factory colour settings of the device, professionals carefully set up the lighting and calibrate the hardware, and not only manage, but also measure colour at all stages of the photographic and imaging processes, from capture through to application.

The importance of colour accuracy in art and heritage studies cannot be overestimated. It is perhaps surprising that black-and-white prints still prevail in many art books, even those on painting and colour studies. The popular book, *Art of Seeing* by John Berger, frequently reprinted by Penguin, may serve as an example. The superior quality of print reproduction of art, that has become available since the 1990s, is a result of years of research into colorimetric imaging. Notable international research projects in this area included VASARI (mentioned in chapter 8), MARC and MARC II, and CRISASTEL, carried out by major European information technology companies in association with museums and conservation institutes from 1989 through the 2000s. Prototype scanners enabling direct digitization of a painting, without the intermediary of photographic material, were developed and implemented at the Doerner Institute in Munich, the National Gallery in London, and the Uffizi Gallery in Florence. Another lasting effect of these historic imaging developments is the service known as Print-on-Demand, offered by some museums to visitors and online: customers can order a superior quality print, on canvas-textured paper, of a painting of their choice. CRISASTEL also pioneered the transmission of large image files over a network, today taken for granted. Black-and-white photography is art in itself, but one can only be pleased that greyscale prints, so common in the past, no longer predominate in newly created visual records.

There is more to colour than meets the eye. The colour that is invisible to the human eye is a subject of aesthetic theories of art that explores the effect of mental "after-images" that we can see, with the eyes closed, having previously stared at the sun or another light source. Władysław Strzemiński's abstract *An After-image of Light. A Lady at the Window* (ca. 1948, Museum of Art, Łódź) evidences such an artistic exploration. COSCH's scope of scientific research into colour extended to spectral imaging techniques and devices in the visible (380–750nm), near infrared (750–1000nm), and infrared (1000–2500nm) ranges. "The combination of digital imaging with spectroscopy has expanded point-based, or one-dimensional (1D) spectroscopic techniques. Imaging spectroscopy provides the ability to distinguish and map the spatial distribution of materials over an entire object, extract reflectance spectra for the identification of materials, calculate colour, enhance and reveal underdrawings, detect changes in composition, and identify damage and past conservation treatments" (p. 142). A group of scientists and other researchers within the COSCH network carried out a Round Robin Test (RRT), discussed in chapter 8, to assess the current diversity of systems and methodologies, aiming at more standardization and quality control.

Space

"Colour is all," believed Chagall. "When colour is right, form is right."[3] This artistic observation points towards one of the most pertinent relationships in the arts and in our experience of the external world, that between colour and form. The COSCH network's understanding of space was predominantly scientific. In the context of COSCH research interests, space is synonymous with the three-dimensionality of material objects: the geometry of the object, including architecture and other physical structures. Therefore, space in this book is primarily considered as measurable, geometrical properties of material objects, and a subject of 3D optical metrology. Geographical terrain, or phenomenological experiences of space, or

3 Citation after Chagall "Colour Is Everything," Spring exh., William Weston Gallery, London, 16 April 2015, http://www.williamweston.co.uk/exhibitions/items/133 (accessed 15 October 2016).

anthropological approaches to a place, all of which are relevant to cultural heritage, were outside the scientific objectives of COSCH research, although they had to be addressed, if only marginally, in the context of 3D historical visualization (COSCH Working Group 5). Time, inherent to the experience of space, is considered in the same context, and referred to, for convenience, as the 4D presentation of cultural heritage (chapter 5). A dedicated COSCH working group was preoccupied with spatial object documentation: the methods and instruments for the acquisition and processing of 3D data. Photogrammetry, 3D laser scanning and total station surveying, structured light scanning and Structure from Motion are amongst 3D sensing techniques employed in COSCH studies, covered in the chapters that follow. Historical visualization of cultural heritage was generally seen as a by-product of 3D data acquisition and processing. Arts and humanities scholars and the general public are likely to evaluate visualization, based on its appearance and realism of rendering, rather than its geometry. The characteristics of these and other methods are explained and discussed; ample exemplars of applications to cultural heritage are provided, with further references to significant non-COSCH projects and literature. One should bear in mind that Euclidean space and linear time, both deeply rooted in Western cultures, are amongst other possible concepts of past cultures.

Science and Technology

The relationships between science, technology, and cultural heritage, described as "inexorable" (Rogerio-Candelera 2014, xi) have been widely researched (MacDonald 2006; Barber and Mills 2011; Stanco et al. 2011). The COSCH network was established as a trans-domain COST Action (TD 1201) in Materials, Physical, and Nanosciences. Participating scientists and engineers included experts in material sciences, conservation, chemistry and physics, photonics, imaging and a range of other fields in computer science. The participation of humanities scholars and other non-scientists in a network dedicated to materials, physical, and nanosciences is an unusual feature.

The material and technology used in the making of an artefact determines its formal characteristics, as well as aesthetic qualities and its value. One of the COSCH working groups focused on the conservation science of the surfaces of material objects. The case study described in chapter 4 concerns the examination of art materials that led to their identification, supporting the dating and attribution of the work, namely medieval wall paintings rediscovered under modern plasters. Art materials and techniques may also, albeit not necessarily, determine the cultural and artistic significance of the work (both are subject to fashion and other fluctuating, subjective factors), providing insights into the technical history of cultural heritage. Outdoor Impressionist painting, characterized by impasto, would not have been possible without the invention of quick drying oil paint. Le Corbusier's architecture would be very different without reinforced concrete. Technology affects the preservation, conservation, study, and communication of material culture.

Long before the digital era technology was being applied in the conservation of art and architecture to great, albeit occasionally disastrous effect (chapter 4). For example, microscopic analysis of pigments and dendrology helped the authentication and dating of paintings on wooden panels; and the application of photogrammetry to architecture was applied, among others, in the rebuilding of the Castle Howard in Yorkshire, England, after it was partly damaged by fire in 1940 (Thompson 1962). Accurate dimensions for restoration were calculated from available old photographic prints that had been taken with no photogrammetry in mind.

An important area of COSCH research has implications for *all* computer-based activities, namely algorithms. Invisible to most users, algorithms determine the effectiveness of applications of digital technology. Much work, led by a dedicated working group, was carried out to offer guidance in this difficult area. The problem of calibration, for example, is much greater than mentioned above. "The main problem with calibration accuracy is that it is both device dependent and application dependent. Thus, the calibration process used for a laser scanning system may differ from the calibration processes used for point-based spatial recording, spatial fringe projection, spatial photogrammetry or tactile measurement" (Trémeau and Murphy 2016, 2).

Good understanding of algorithms that support optical recording and examination of material objects was fundamental to the correct representation of the relevant know-how. So in the COSCH Knowledge Representation ($COSCH^{KR}$), described in chapter 9, "The COSCH Algorithm Selection Module (COSCHASM) has been defined formally to represent several processing chains used in Cultural Heritage as a hierarchy of algorithms to denote the types (from acquisition to visualization), properties (e.g., accuracy) and inter-relationships (e.g., between parametric factors) of algorithms used for a given task (e.g., 3D reconstruction of a Greek vase in the Kantharos case study exemplar). The main specificity of the COSCHASM is that it is aimed at end-users (who are non-experts in computer vision) in order to help them to find/select the best sequence of algorithms corresponding to their application" (Trémeau and Murphy 2016, 8).

As with other areas of study, digital technology has exponentially enhanced and expanded applications, while raising new issues. Digital data captured for one particular purpose may be reused for another. However, the advantages of applying digital technology to the examination and documentation of material culture cannot be taken for granted. The benefits need to be evidenced. Technical innovation must acknowledge earlier relevant research and be sympathetic to those traditional research methods that continue to be effective. A combination of different research methods enhances the critical evaluation of the chosen approach, often bringing a better understanding of the data under investigation and, ultimately, new insights into the subject of study. Chapter 4 demonstrates the significance of archival research conducted concurrently with a technical investigation of historic wall paintings. The virtual reconstruction of a fragmented ancient vase, covered in chapter 2, would be futile unless based on archaeological knowledge and earlier comparative studies of Greek pottery, including those communicated through text and hand drawings.

The limitations of digital technologies and related know-how need to be communicated to stimulate further research and this is one of the aims of this book. Another aim is a transparent account of areas prone to errors, including the failures of our research, to prevent others from repeating the same mistakes and take research forward. The aim of integrating spatial and spectral instruments and software, currently used independently, and to enhance the fusion of heterogeneous data, remains an ambitious and difficult goal. Many issues within individual technologies remain. Two studies in particular, those of silver coins and the Round Robin Test, described in chapters 3 and 8 respectively, applied a range of recording and analytical technologies to the same objects in order to compare and evaluate how results depend on a particular setup or operator. A number of problems were encountered due to: differences between instruments, software, and algorithms; the heterogeneity of captured data and file formats that can be generated and the profusion of standards and different claims to best practice. As pointed out in chapter 1,

> One should not underestimate the importance of describing and documenting well the used measurement methods and procedures, as these contribute to the determination and understanding of the overall quality of the measurement results and, at the same time, to a better analysis and interpretation of the measurand—the cultural heritage object in context—in this case. . . . "repeatability" measures the variation in measurements taken by a single instrument or operator under the same conditions (including same location, instrument, operator, procedure) and repetition over a short period of time, "reproducibility" measures the variation in measurements under a reproducibility set of conditions (e.g., different location, instrument, operator, procedure). Put simply, it measures the ability to replicate the results of others. (p. 6)

The COSCH network was primarily preoccupied with applied optical technologies. This book makes clear the connection between technology and its application(s). In the second, strictly technical part of the book, selected technologies employed in COSCH case studies are explained in the wider context of international research, with additional examples and suggestions for further reading. The explanations are aimed at both specialist and non-specialist readers. Each entry consists of a definition which introduces the basic principle of the technology or method, followed by a more detailed, specialist description and selected examples of significant projects.

Methodology

Conference papers exploring the relationships between cultural heritage and technology constitute a considerable part of the literature in this area. Published relatively quickly, conference proceedings are indispensable sources for the latest innovation. Significant collections of diverse practice-based academic papers have been published in book format (Rogerio-Candelera 2014; Ioannides and Quak 2014; Stylianidis and Remondino 2016). Such collections, broadly responding to a generic theme in cultural heritage and technology, are not necessarily consistent in approach and research methodology. The collection of papers in this book is deliberately different. The chapters present the outcomes of carefully designed COSCH case studies dealing strictly with applications of optical technologies, spatial and spectral, to the study of material cultural heritage. In 2012 COSCH issued a call for proposals for case studies that would adhere to the scientific and interdisciplinary objectives of the Action. The call was issued with relevant methodological advice and references to standard literature on case study research.

Discussions held during the course of the COSCH Action showed that it is quite common to confuse a case study with use case or an exemplar application. A case study and use case are not synonymous with an exemplar (typically of a particular practice or project). Case studies and use cases are both forms of detailed empirical research into a particular situation and behaviour. Both require data collection and data analysis. To demonstrate the reliability of a case study, or use case, it is necessary to demonstrate that the operations can be repeated with the same results. Should one expect the same accuracy from instrumentation of comparable specification, irrespectively of how and where the recording took place? Is the human operator an affecting factor? COSCH case studies have demonstrated that this is far from being straightforward. The COSCH Round Robin Test (chapter 8) served as an experiment conducted in multiple laboratories to understand better the factors that affect the results of imaging spectroscopy techniques, applied to the same artefacts, in particular the differences in the instrumentation and data acquisition methods, and their effects on the accuracy and reliability of the acquired data. The COSCH case study of historic silver coins (chapter 3) involved experimenting with various spatial recording and analytical technologies, applied to the same test coins, in order to compare the quality of the acquired data.

In applied technical research a use case is a method in software and systems engineering. It seeks to establish how a human or machine system is able to achieve an objective specified *a priori*. Case study research combines quantitative and qualitative methods with the emphasis on human participants, and is more common in social sciences. It also seeks to determine how one condition leads to another (internal validity), but only for explanatory or causal studies. The other types of case study research, descriptive or exploratory, may be designed differently, but should equally demonstrate "external validity, i.e. define the domain to which a study's findings can be generalized" (Yin 2014, 46). Bearing in mind the interdisciplinary complexity of research into cultural heritage, the choice of case study methodology offered the required flexibility, without jeopardizing the integrity of individual disciplines and without curtailing innovation. Importantly, six types of sources that may be used in case study research include the evidence of the physical object, which is critical to the COSCH research covered in this volume. The reader will be able to judge the quality of response to the COSCH call for case studies, and the level of success in adopting this approach while seeking coherence in intellectual complexity and technological diversity. When dealing with this challenge human limitations and financial restrictions played a part. They were manifest in planning, organization, and delivery of tasks in the course of what was generally voluntary work.

Knowledge through Documentation

Documentation is the key concern that connects all the contributions to this book. Documentation is "The already existing stock of information. As an activity, it stands for the systematic collection and archiving of records in order to preserve them for future reference. It can be said: Today's recording is tomorrow's documentation." According to the same source, recording "is in a broad sense, . . . the acquisition of new information deriving from all activities on a heritage asset, including heritage recording, research and investigation, conservation, use and management, and maintenance and monitoring" (Letellier et al. 2007, iv).

Although not a subject of systematic and comprehensive study by COSCH, the formats, standards, and management of documentation were relevant to many COSCH projects. The Roman coin case study (chapter 3) sought to establish connection between historic and current museum documentation practice and heritage science, looking specifically at the relationships between a standard museum object record, technical metadata (such as 3D measurements, results of chemical and elemental analyses), and iconographic records other than 2D photographs. Documentation, both the process of and its outcomes, was variably understood by COSCH researchers as: digitization/recording/surveying/measuring of a historic material object of cultural significance. All these terms were used interchangeably, prompting a need for in-depth, critical discussion of terminologies used by the COSCH interdisciplinary community, and generally in cultural heritage research (see chapter 1). The clarity of discrete disciplinary differences was essential for effective communication (see chapter 10).

Technical documentation that employs scientific methods of recording and analysis may be produced independently of historical and other cultural knowledge about the object. A basic responsibility of the museum, and other custodians of cultural heritage, is to keep records of every object in their care, even if the object is obscure to scholars and likely to remain in store awaiting study. This critical legal and conservation objective continues to be met predominantly through photography, manual measurements, and notes. The benefit of applying advanced optical recording technologies to cultural heritage is best manifested when—apart from recording the object's appearance and condition—the process also serves critical investigation with the potential of bringing about new insights into the interpretation of the object: its authenticity, provenance, historical use, and transformation. Comprehensive object documentation consists of technical records based on scientific information, alongside all other available records (visual, textual, audio, and in other formats) of the object, pertaining to its material and immaterial aspects, past and present. "It is the cultural heritage question one wishes to answer that determines the key properties that need to be documented [or recorded] and described in any given situation for a given cultural heritage object," state the authors of chapter 1 (p. 5). COSCH researchers were broadly in agreement that the best method of documentation may only be chosen based on the specific, object-related questions. Choosing the provider of the appropriate technology requires some level of familiarity with the technical options possible, and sustainability of outcomes, a familiarity which the object custodians may not have.

As part of its aim to foster applications of optical technologies for the documentation of material cultural heritage, the COSCH network sought to structure relevant information about applications, methods, and instruments. Based on information science and semantic technologies, a formal representation of this specialist interdisciplinary knowledge was discussed, designed, and implemented through a dedicated online platform, $COSCH^{KR}$ (see chapter 9 and http://cosch.info/coschkr-treeview). The responsiveness of the ontology to ever progressing knowledge—scientific, technical, and cultural—proved to be a true intellectual challenge. The design and development of the $COSCH^{KR}$ was one of the areas of

COSCH research that required a good understanding of conservation and scholarly documentation practices; good enough to be able to determine how advanced spatial and spectral technologies may effectively support cultural heritage professionals and scholars in their practice.

Art and science are forms of knowledge. A few glimpses into the aesthetic thought and practice of a single artist, Chagall for example, suffice to confirm the complicated, multidimensional nature of colour and space. Some dimensions cannot be measured. Owing to this complexity, optical technologies can only offer a part-solution to comprehensive object documentation. However, the significance of this contribution cannot be stressed enough. Recording yields data which, through processing and interpretation, bring about information that is required to acquire new knowledge. The realization of the significance of interpretative processes for the advancement of knowledge results in the necessity to record not only the process of recording, as advocated above, but the entire research process. Therefore paradata, recorded alongside metadata, are critical to scholarship, even more so to those digital scholarly processes which progress from one step to another without leaving behind visible traces of how one has arrived at the result. Paradata and other forms of *scholia* are necessary to ensure the transparency of the process, to enable its repetition and revision (Bentkowska-Kafel et al. 2012).

The WinSOM software, designed for the solid modelling of Winchester Old Minster, cost several times more than the funding of the COSCH network which, some thirty years later, has facilitated the studies of some 240 international researchers over four years. Applications of cutting-edge technology may be worth the great effort and investment even if they are eventually superseded by better solutions. The contributors to this book make persuasive arguments about the long-term, cognitive benefit of the digital documentation of cultural heritage, the value of which is independent of the technology that enabled new insights into the subject of study. We hope that our readers, specialists and non-specialists alike, find the chapters herein, which are representative of our work, valuable for developing and recording their own digitization projects and that they spark new research questions for the cultural heritage community.

The companion website with additional material, some interactive and in 3D, can be found at https://coschbook.wordpress.com.

Part I

COSCH CASE STUDIES

Chapter 1

AN INTERDISCIPLINARY DISCUSSION OF THE TERMINOLOGIES USED IN CULTURAL HERITAGE RESEARCH

VERA MOITINHO DE ALMEIDA, STEFANIE WEFERS, and ORLA MURPHY

ABSTRACT

Accuracy, artefact, feature, precision, reconstruction, resolution, texture, uncertainty are words central to many discussions of the documentation of cultural heritage. This terminology, whilst broadly understood across the disciplines, is often misunderstood due to its specific use in particular cases. An interdisciplinary dialogue conducted over a period of years and comprising experts in a range of fields—art history, colour science, engineering, semantics, mathematics, cultural heritage, museum studies, and others—has yielded a challenging discussion document that considers the thorny issue of a shared understanding of a set of keywords. On occasion our perceived shared language is not shared at all but reveals—at times through subtle nuance, and yet at times through gaping chasm—the disciplinary subjectivities we hold unbeknownst to ourselves. Mutual understanding of some of these key terms is central to any newly engaged, participatory transdisciplinary endeavour that seeks to develop critical methods for the documentation, analysis, preservation, and sharing of cultural heritage objects outside the traditional disciplinary silos. This chapter charts the interdisciplinary discussion towards a common understanding of terminologies used in cultural heritage. It is a discussion that recognizes critical differences or common misuse, and aims to contribute to a shared understanding that may be useful for all knowledge domains in the field. The chapter summarizes the work of a number of Think Tanks conducted by Early Career Investigators participating in the COSCH network.

Keywords: cultural heritage, interdisciplinary research terminology, metrology, humanities, digital documentation, COSCH

Introduction

The digital documentation of material cultural heritage is a multidisciplinary task and often involves experts in spectral and spatial recording, and Information and Communication Technology (ICT). When generating digital representations of objects of cultural heritage, a shared understanding is necessary to develop suitable and user-oriented solutions. However, reaching a shared understanding is complex. It begins with a clear definition of the project's aim(s), including the explanation of concepts, terms, and procedures that may be unknown to some project partners. These first steps may seem obvious and should be the basis not only for multidisciplinary projects, but for all projects. However, these tasks are more multifaceted in multidisciplinary projects as, in addition to unfamiliar disciplinary terminology, each project partner might use terms that are common to various domains, but may have inherently different meanings.

Current relevant policies of the European Union, as evidenced in many documents of the Horizon 2020 programme, require researchers: "to foster, harness and leverage collaborative interdisciplinarity . . . as a key priority for EU research and innovation policy . . . in order to come up with quicker and effective solutions to complex grand challenges and analyses of complex systems that call for crossing departmental boundaries and inter-disciplinarity to generate new knowledge of transformative power" (Allmendinger 2015, 4).

Through discussions between Early Career Investigators (ECIs) participating in the COST Action TD1201, Colour and Space in Cultural Heritage (COSCH), terms that were considered crucial for a common understanding of projects documenting material cultural heritage with spectral or spatial optical recording technologies, were identified. The ECIs were from spectral, spatial, and ICT domains, as well as from archaeology, conservation, art history, and other disciplines involved in cultural heritage research. Research into the definition of the term yields useful insight: in *Disciplinarities: Intra, Cross, Multi, Inter, Trans*, Jensenius (2012) defines interdisciplinarity as "integrating knowledge and methods from different disciplines, using a real synthesis of approaches." Using this proposition as a starting point, the COSCH Think Tanks aimed to reveal semantic discrepancies between disciplines through discussion. Benefiting from their varied backgrounds, the participating researchers worked together towards a more useful interdisciplinary approach, and indeed towards a transdisciplinarity which Jensenius (2012) defines as "creating a unity of intellectual frameworks beyond the disciplinary perspectives."

Identified Key Terms

More than 130 terms were identified as being both particular to singular domains and problematic due to their varied or ambiguous meanings across disciplines. A working document was created listing the identified terms. Each term was accompanied by a short explanation, defined as plainly as possible, and addressed to those not familiar with the respective term. A figure was added to these definitions where possible, and a reference to an explanation in the specialist literature. The list encompasses (1) spatial and spectral recording techniques, systems and devices, such as those covered in the technical section of this book, (2) terms related to methods, processes, and workflows, (3) characteristics/parameters of quality, (4) general terms used in cultural heritage domains and in cultural heritage science broadly, and (5) characteristics of surfaces of material cultural heritage.

Within this contribution we would like to focus on some of those considered most relevant by the authors.

Key Terms Which Are Domain Inherent and Might Be Unknown to Collaborating Partners from Other Disciplines

Objects of cultural heritage encompass a vast variety of materials, colours, shapes, textures, and patterns amongst other characteristics. Understanding these, their roles, and their combinations allows insight to the interrelationships between them, as well as insight into issues which may include, but are not restricted to: material provenance, manufacturing techniques, use-wear, knowledge networks, and human mobility. Conversely, this understanding may also assist in predicting and/or understanding their occurrence in new contexts, their reuse. For these reasons, the need and concern for the documentation and description of cultural heritage objects is unequivocal; that these methods are reliable, that procedures and techniques are internationally accepted is also a "given." It is the cultural heritage question one wishes to answer that determines the key properties that need to be documented and described in any given situation for a given cultural heritage object.

Consequently, proper use and reference when discussing accuracy, precision, resolution, and uncertainty, and related terms, are very important when working with any type of measurement technology—may it be a calliper or a scale, or even a 3D or hyperspectral imaging system—as inaccurate, imprecise and low-resolution measurements with a high level of uncertainty may most certainly lead to erroneous interpretations of cultural heritage objects. Following COSCH's aims, our focus here will be mainly on spatial and spectral related issues. Hence, before discussing these four selected keywords, we will first introduce some related metrological concepts and terms to enable a better understanding of the context.

Basic Metrological Concepts and Terms

Metrology is the science of measurement and its application. As such, it "includes all theoretical and practical aspects of measurement, whichever the measurement uncertainty and field of application" (ISO 2004, 13).

Once the aim of a given work or project has been set out, defining the "measurand" is the first step of any measurement procedure. According to ISO (2004) and JCGM (2012), the term measurand refers to the quantity intended to be measured—regarding material cultural heritage, this could, for instance, refer to the weight or form of an artefact, its colour, or even its chemical and elemental composition that is to be measured. Whereas the term "measurement" refers to the process of obtaining information about the magnitude of a specific quantity, where the information is the result (e.g., process: object is weighted on a scale; result: 62 g). In some cases, however, the information may consist of a set of quantity values, typically summarized as a single quantity value (i.e., an estimate, such as the average or the median of the set) and a measurement uncertainty (in this case, if considered negligible the information may be reduced to a single quantity value), see below.

Every measurement implies a measurement method and respective procedures. The "measurement method" consists of a generic description of a procedural structure used in a measurement, where the "measurement procedure," sometimes called standard operating procedure (SOP), is documented in enough detail in order to enable an operator to perform a measurement. One should not underestimate the importance of describing and documenting well the used measurement methods and procedures, as these contribute to the determination and understanding of the overall quality of the measurement results and, at the same time, to a better analysis and interpretation of the measurand—the cultural heritage object in context, in this case. Notwithstanding these issues, while "repeatability" measures the variation in measurements taken by a single instrument or operator under the same conditions (including same location, instrument, operator, procedure) and repetition over a short period of time, "reproducibility" measures the variation in measurements under a reproducibility set of conditions (e.g., different location, instrument, operator, procedure). Put simply, it measures the ability to replicate the results of others. Repeatability and reproducibility are strongly related to precision, as we will explain. By implication, one can understand the "metrological traceability chain" as a chain of alternating systems with associated procedures and standards, from a measurement result to a stated metrological reference. This, in turn, enables results to be compared because they can be traceable to the same stated reference (ISO 2004).

Of course, both measurand and the type of measurement to be performed (as well as scale of analysis, besides other issues) will most certainly dictate the type of measuring system and instrument that should be used. So, we have a "measuring system," which consists of one or more measuring instruments and other devices or substances used for making measurements (ISO 2004; JCGM 2012)—where every measurement should require as a precondition a calibrated measuring system, possibly subsequently verified (ISO 2004). And we have "measuring instruments," which can be identified or classified in distinct categories "according to unique metrological and technical characteristics that may include the measured quantity, the measuring range, and the principle or method of measurement" (OIML 2011, 19).

Accuracy

We return to the set of key terms we originally intended to discuss: accuracy, precision, resolution, and uncertainty.

The term "accuracy" is well defined in the literature (ISO 2004, 2012; Letellier et al. 2007; JCGM 2012; *English Oxford Living Dictionary* n.d.; *Merriam-Webster Dictionary* n.d.; *Encyclopaedia Britannica* n.d.) and, as such, it should not appear "abstract" for applications to cultural heritage. Accuracy refers to the degree of conformity of a measurement, calculation, or specification to the correct or truth value, or to a standard or model. Accuracy can then be determined as length measurement error of known distances in a measurement volume. In other words, the higher the accuracy, the closer the measurement result is to the true or reference object/value (JCGM 2012). Measurement conditions are also well described for a number of distinct systems and values may therefore be compared between systems. Internationally recognized standards for accuracy determination of optical 3D measurement devices have been established in VDI/VDE 2634 (2002, 2012a, 2012b) and for colour measurements in ASTM E2214 (2002, 2012). Corresponding guidelines are also well established in the industrial field. Similarly, standard procedures exist for measurement of surface roughness, waviness, and lay (i.e., rugosity and flatness) (ASME 2010; ISO 2012; Moitinho de Almeida and Rieke-Zapp 2017).

Resolution

Concerning the resolution of a measuring system, it is defined by the smallest change in the value of a measured quantity that can be meaningfully distinguished (ISO 2004; JCGM 2012).

Spatial resolution is usually understood as the smallest distance between two measured values (e.g., number of pixels per unit of length/area, number of

3D coordinates per unit of area). Nevertheless, and taking 3D spatial resolution as an example, individual 3D coordinates may represent smaller or larger areas on the object depending on the type of measuring system used. Fringe projection systems can generate one independent 3D coordinate per camera pixel, while correlation based photogrammetric techniques analyse 2D image patches for 3D coordinate calculation. The larger the correlation window is, in the latter case, the less sharp detail will show up in the resulting 3D model. Edges will appear more rounded and details lost (Kersten et al. 2016). Hence, one can understand why the number of 3D points in a model is not a good method for judging the amount of information in it (Moitinho de Almeida and Rieke-Zapp 2017). Consequently, spatial resolution should be based on the ability of, for instance, a 3D scanner to acquire separate 3D coordinates of closely-placed features (see below “feature”) or a camera to produce separate image pixels of closely-placed features. Similarly, the resolution of images (AAT 1988–) and display devices (JCGM 2012), such as screens, refers to the smallest difference between its indications that can be meaningfully distinguished.

As to “spectral resolution,” it can be understood as the smallest width of the electromagnetic spectrum which can be distinguished by the spectral system (the ability of a spectrometer to separate adjacent peaks in a spectrum). Spectral resolution is often combined with the description of instrument measurement range, which describes minimum and maximum wavelength detectable by it. So, for instance, an imaging system which is capable of detecting electromagnetic radiation in the range of 400–480 nm with resolution of 10 nm, shows the level of radiation in 8 partitions with each integrating radiation with wavelengths differing no more than 10 nm.

Precision

“Precision” is defined by the international standard JCGM 200:2012 (JCGM 2012) as the closeness of agreement between quantity values obtained by replicate measurements of a quantity, under specified conditions. Repeatability and reproducibility are ways of measuring precision. Precision is usually expressed numerically by measures of imprecision, such as standard deviation, variance, or coefficient of variation under the specified conditions of measurement. In short, the higher the precision, the higher the similarities between different measurements of a same object. Notwithstanding, a measuring instrument can be very precise but inaccurate, or accurate but imprecise; or very precise but have low resolution, or have high resolution but be imprecise; or any other possible combination between accuracy, precision, and resolution. Moreover, as previously mentioned, there are technical considerations, operational imperatives, and specific conditions which must be taken into account as they can interfere in the results (Moitinho de Almeida and Rieke-Zapp 2017).

Uncertainty

Measurement error is ubiquitous in scientific work. According to the International Organization for Standardization (ISO 2004, 16–17), "uncertainty" of measurement is a parameter which enables us to characterize quantitatively "the dispersion of the quantity values that are being attributed to a measurand" (i.e., the knowledge about the measurand), based on the information used. The evaluation of measurement uncertainty may be either based on the "statistical analysis of quantity values obtained by measurements under repeatability conditions" (type A); or theoretical, this is to say, by means other than statistical analysis (type B)—e.g., associated with published quantity values or with a quantity value of a certified reference material; determined by an instrument's calibration certificate (i.e., instrumental uncertainty), by the accuracy class of a verified measuring instrument, or by limits deduced through personal experience. It is worthwhile noting that the calibration of an instrument—along with the calibration of the measurements (should the instrument enable this procedure)—is an essential part of the process to ensure data integrity.

Figure 1.1. Example of sources of measurement error in 3D scanning that lead to uncertainty of measurement results (Moitinho de Almeida 2013).

Hence, when planning the measurement method it is fundamental to consider measurement error and the uncertainty of measurement results issues caused by environmental, instrumental, operator, measurand, among other factors (fig. 1.1) (Li 2011).

Terms Which Are Commonly Used That Are Ambiguous

Four terms—artefact, feature, reconstruction, and texture—are presented briefly on the one hand from a cultural heritage perspective and on the other hand from a technical perspective, illustrating the dimensions for a potential misunderstanding within interdisciplinary discussion and projects.

Artefact

Focusing on the spatial and/or spectral recording of cultural heritage objects, the first term to be explained is "artefact" which has to be seen in context of the term "cultural object." The latter is defined as an object significant to the archaeology, history, architecture, science, or technology of a specific culture (UNESCO 2003a, 2016a). Cultural objects may be classified as intangible (e.g., traditions, social practices, performing arts, knowledge, and skills) or tangible, and in this case as immovable or movable. Examples of cultural immovable objects are built and natural monuments, movable objects are ecofacts and artefacts (UNESCO 2016a, 2016b). Ecofacts constitute a large class of natural materials that have relevance to human action and behaviour in the past—e.g., pollen, plant remains, charcoal, animal bone, coprolites, residues. Whereas the term "archaeological artefact" refers to any portable object manufactured, modified, or used by humans (AIA n.d.)—e.g., lithics, sculptures, potsherds, or coins.

The context in which an archaeological artefact is found is of special interest for its analysis and interpretation, as it may enable a more precise dating and give evidence for social actions (e.g., manufacture, usage, discarding). Furthermore, the information about its find spot may enable the researcher to put it into a broader context, for example, by mapping similarities, dependencies, and connections to other contexts, artefacts, and evidences, towards a better understanding of past societies. As a rule, one may say that the more information about an artefact and its context is available the more valuable it is for archaeological research (Jones 2003; Eggert 2013). However, more than data quantity it is data quality and adequacy that is needed (Moitinho de Almeida 2013).

For museum objects, the Getty *Art & Architecture Thesaurus* (AAT 1988–) uses "cultural artefact." In the cultural heritage field, a "digital artefact" is usually understood as a digital surrogate/representation of a cultural heritage or archaeological artefact—an example of this could be a 3D digital model of a Roman amphora.

When referring to computers, electronics, and optics, "artefacts," more commonly known as "digital artefacts," "computational artefacts," or "noise" (although these terms may as well convey other meanings) are unintended and unwanted errors, distortions or other aberrations that occur due to transmission errors or signal processing operations (Horak 2008)—that is, during the acquisition, transmission, processing, conversion, or compression of analogue or digital signals or data—which are typically caused by a limitation or malfunction in the measuring system or software. Artefacts are not always easily detectable, but can sometimes be encountered in digital images, 3D scanned models, or spectral data, amongst other research areas.

Feature

The term "feature" is often used in archaeology with two distinct meanings, either referring to "a set of contexts" (Carver 2005, 82) in which archaeological evidence is discovered, or to the distinctive parts, characteristics, or attributes of archaeological evidence. Notwithstanding this, both meanings of "feature" are likely to give insight into former human actions. An example of feature as "a set of contexts" could be a number of holes dug in the past to hold posts for constructing a pile-dwelling (or stilt house) and refilled later on due to the destruction of the house. These two events (i.e., construction and destruction) could be interpreted in the present, after the detection and analysis of discolouration patterns of the soil. However, such features, or individual contexts, may contain one or more artefacts, ecofacts, or any other type of archaeological evidences, where each one has in turn its own features (here meaning distinctive parts, characteristics, or attributes)—for instance, an artefact with a specific colour, shape, texture, pattern, material, etc. (Eggert 2013; see various chapters in Renfrew and Bahn 2005).

In computer vision, the term "feature" coincides to a certain extent with the second meaning aforementioned—i.e., "distinctive parts, characteristics or attributes"—as it is understood as an element (or part of data) in image or 3D data which ideally can be automatically distinguished and described using processing algorithms. Such elements can be used for image (or 3D data) matching and stitching using corresponding points, pattern recognition and object classification. Features can be extracted by means of intensity, hue, curvature, and other parameter analyses (Roth 1999; Lowe 2004; Mikolajczyk and Tuytelaars 2009; Hołowko et al. 2014; for typical computer vision applications see: Hassaballah et al. 2016).

Reconstruction

For much of the literature found in the cultural heritage field (The Heritage Canada Foundation 1983; Seville Principles 2011; AAT 1988–), "reconstruction" involves the construction of a new object, building, or structure, that represents, as closely as possible, a cultural heritage object that has been entirely or partially lost. These references seem to be very limited. They only consider a number of physical and visual reconstructions, apparently ignoring all non-visual and immaterial cultural heritage. In any case, reconstructions, such as computer models, or works in other media, which enable a proposed representation of how some thing or place may have been or looked, an activity had been done, an implement was used, or some actor may have behaved at a previous time, are carried out on the basis of archaeological, historic, literary, graphic, and pictorial, or other similar evidence. Reconstructions raise concerns in many instances about accuracy and uncertainty, especially when certain features are based on conjecture instead of clear evidence. To follow AAT (IDs: 300387703 and 300389893), "digital reconstruction"—also referred to as "virtual reconstruction"—is a specific branch of reconstruction, in the sense that it makes use of computers and appropriate programming language or software to construct digitally, or "fill in the losses and lacunae" of missing digital data, including those of digital representations of cultural heritage objects. Physical (i.e., real world) and digital reconstructions (e.g., experimental archaeology and computer simulation methods and techniques) have already demonstrated their usefulness in helping to gain practical knowledge and in testing theoretical hypotheses (Ingersoll et al. 1977; Skibo 1992; Terradas and Clemente 2001; Hopkins 2008; Moitinho de Almeida 2013; Moitinho de Almeida et al. 2013; Pfarr-Harfst and Wefers 2016).

Texture

Texture is usually defined as those attributes of an object's surface having either visual or tactile variety, and defining the appearance of the surface (Tuceryan and Jain 1998; Fleming 1999; Mirmehdi et al. 2008; Engler and Randle 2009; AAT 1988–). Hence, it is useful to distinguish visual appearance (e.g., colour variations, brightness, reflectivity, and transparency) from tactile appearance (e.g., microtopography, soil texture).

Visual appearance is perceived as complex patterns composed of spatially organized, repeated subpatterns, which have a characteristic, somewhat uniform appearance, under certain viewing and measurement conditions (Leung and Malik 2001; Szczypinski et al. 2009). For instance, an inlaid marble floor from a Renaissance house is differently perceived by a human observer depending on the viewing direction, light source, and a range of other variables. In digital/electronic imaging, an "image texture" can be understood as a two-dimensional image representation of the surface texture under certain conditions—and we have already explained that different conditions may likely yield different results, in this case, of textures. While "texture mapping" consists in applying a two-dimensional image file containing texture, colour (this can also be applied as "colour per vertex"), or surface detail to a 3D model or computer-generated graphic (AAT 1988–)—other types of mapping include height, bump, normal, displacement, reflection, specular, and occlusion.

The real surface of an object can be defined as a set of features which physically exist and separate the entire workpiece from the surrounding medium (ISO 1996), where the texture of the surface—here, its topography, as a scale-limited complex combination of spatial frequencies—is just one of its key features. In simple terms, tactile variation can be understood as the geometrical irregularities that emerge when considering roughness, waviness, and lay—a "3D texture." ASME (2010) (fig. 1.2) defines roughness as the finer spaced irregularities of the

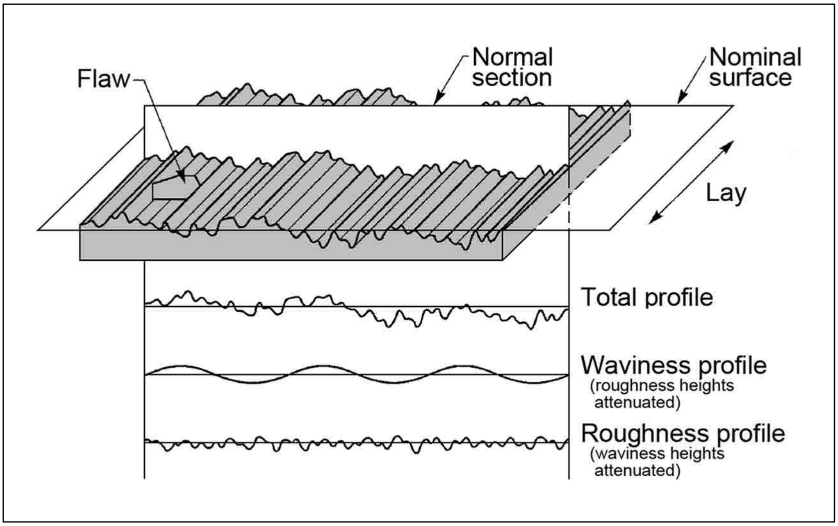

Figure 1.2. Schematic diagram of surface characteristics. Adapted and reprinted from ASME B46.1-2009, by permission of the American Society of Mechanical Engineers. All rights reserved.

surface texture that usually result from the inherent action of the production or material conditions; waviness, as the more widely spaced component of the surface texture, where roughness may be considered as superimposed on a wavy surface; and finally lay, as the predominant direction of the surface pattern, ordinarily determined by the production method used. As to “soil texture,” it refers to the percentage of different sizes of particles smaller than 2 mm in a volume of soil (SCS-USDA 1993), not necessarily taken from the surface of the ground.

In general, texture can be characterized either from physical or digital data, from macroscale to nanoscale, using advanced metrology methods and techniques, and by means of 2D or 3D imaging contact or non-contact instruments, which span a wide range and resolution (Moitinho de Almeida 2013).

Example Scenario

As an example, we would like to implement the terms explained above on the basis of the aims and outcomes of an interdisciplinary three-year project (2010–12) “Der byzantinische Mühlen- und Werkstattkomplex in Hanghaus 2 von Ephesos (TR)” (The Byzantine milling and workshop complex in Terrace House 2 of Ephesos, Turkey) (www.rgzm.de/ephesos).

The aim of the project was to investigate the Late-Antique/early Byzantine (late third century to early seventh century AD) water-powered workshops in Terrace House 2 of Ephesos, Turkey, focusing on its construction including the type, number and capacity of workshops and machines powered by varieties of waterwheels, their duration of use and reasons for their abandonment including the investigation of artefacts for absolute dating and in order to understand the economic impact of the workshops through provenance analyses of raw materials (Mangartz and Wefers 2010; Wefers 2015, 2016).

This entire feature is located on a slope with an altitude difference of ca. 30 m. It was completely covered with earth until it was excavated in several archaeological excavations carried out in the 1960s, ’70s and ’80s. It is constructed of stonewalls up to a height of 5 m and preserved in relatively good condition. Several archaeological artefacts, such as coins, potsherds, millstone fragments, among many other types of evidence, have been found and are now stored in archaeological depots. Since 2000, Terrace House 2 is covered by a modern protective roof and is part of the antique site at Ephesos which is open to the public.

The measurand consisted of the entire feature, ca. 100 m × 30 m. The measurement method applied during the 2010 and 2011 archaeological surveys was established according to the aims of the project, expenditure of time on site, logistics, and finally the budget. The measuring system included a combination of three distinct measuring instruments—a tachymeter, a digital single-lens reflex camera (DSLR), and a phase-based laser scanner—where each one has its own specificities and therefore measurement procedures (only a brief overview of methods and procedures used is given here. For a detailed description see Cramer and Heinz 2015; Wefers and Cramer 2014). A tachymeter with an accuracy of 2–3 cm was used to set up a reference system based on the local Ephesos reference system, to enable an adequate alignment of the measurements acquired by the laser scanner. The measurement procedure consisted of setting up well distributed reference points—at least three reference points and targets had to be visible from each scanning position. A DSLR camera (Fuji FinePix S3Pro, Nikon Fisheye 10.5 mm, 4256 × 2448 pixel, 3 times exposure for each view) was used to capture image texture—to be later texture-mapped onto the 3D model—and to generate LDR-360°-panoramic views (12000 × 6000 pixel) for visualization and dissemination purposes.

The phase-based laser scanner (Leica HDS6000) was used to acquire the 3D digital measurements (the 3D coordinates). This instrument’s specifications on accuracy, resolution, precision, and uncertainty of measurement are made available by the manufacturer in the corresponding manual (Leica HDS6000). The measurement procedure was the following: ca. 100 scanner positions were necessary to record the complex overall geometry of the feature. The 3D point cloud resolution was reduced to a minimal point distance of 1 cm, which was sufficient for such a large feature with respect to the project's aims, as well as to the overall data volume and handling. A higher resolution would be required to analyse specific features, such as the roughness—the topography of texture, made up of fine details of the surface of the millstones. Additionally, unnecessary areas, such as the points representing the modern protection roof and computational artefacts, were removed. The individual point clouds were aligned, making use of the reference system produced by the tachymeter. The result of the measurements after post-processing was a point cloud of ca. 500 million points.

The scanner and camera were used one after the other at a fixed position in order to enable combining both 3D data and colour data into one single digital model based on the local Ephesos reference system—an important aspect as further investigations would be conducted outside Ephesos, in Germany. The 3D data set was saved as a document for archiving purposes at the Austrian Archaeological Institute, which is the key stakeholder of the site in Turkey.

However, had the objective been to acquire 3D digital measurements of the aforementioned excavated artefacts for research purposes, the selected 3D measuring instrument would have eventually been different. Taking a coin as an exemplar artefact, which are typically small in size and have fine details, to use a measuring instrument with a resolution of 1 cm would have definitely been inadequate as the smallest geometrical feature expected to be identified should not be smaller than 2 cm, meaning in many cases the whole coin or most of it. More adequate measuring instruments could eventually include 3D close-range structured-light scanner, laser scanner, macro-photogrammetry, digital microscopy, amongst others. Additionally, a good 3D measuring instrument for a coin will be both precise and accurate by acquiring the same 3D coordinates of the coin each time (repeatability, e.g., measurement results: diameter of coin is either 2.819 cm or 2.82 cm each time) and each time they are close to the real coin (e.g., diameter of real coin is 2.8 cm)—within this type of study, the measurement uncertainty may be negligible. All in all, depending on the scientific question prompting the research agenda and the scale of analysis required, among other factors, the accuracy, resolution, precision, and uncertainties of the measurements should be high enough to fulfil the project's or expert's needs for improved scientific documentation and study of the cultural heritage object (Moitinho de Almeida 2013).

A digital model of the workshop complex was reconstructed on the basis of the measurements of the feature and artefacts, as well as archaeological conclusions drawn from comparative studies and logical correlation (Koob et al. 2011). Furthermore, a physical 1:1 scale model of the stone sawing machine was reconstructed for experimental reasons. Experiments with various setups were performed to test hypotheses within the up-to-that-point only theoretical reconstruction of the stone sawing machine. These experiments finally gave evidence for one of the various setups and helped clarify the overall operating mode of the machine, the workshop, and the individuals at the site (Mangartz and Wefers 2010; Wefers 2015).

Conclusion

As a European research forum the COSCH Action aimed to foster a better understanding of the digital recording of material cultural heritage, to define good practice and stimulate research in this area (COSCH MoU 2012). A key challenge in this context was the language which is rich in vocabulary. Words have different meanings, depending on how and where they are used. As in everyday life we have to explain or contextualize certain terms in order to ensure the same understanding and not simply the primarily comprehensible issues when using a foreign language, but particularly for domain knowledge. This is very often the case for international projects where experts might choose English, particularly in a European research context. In a European Research Area (ERA) environment where researchers are encouraged to engage in inter- and transdisciplinary work this linguistic challenge is increased due to terms such as those explained in this chapter.

Further to that and vital to COSCH, the work presented here, which is only a small part of the ECI's work, can be understood as a semantic contribution to the development of controlled vocabularies—to eliminate as much as possible these variations in understanding and interpretation, in order to create machine readable and properly semantically enabled work. The aim of this is to harness the combined intelligence of ECIs across the EU in a variety of domains to eliminate this variability and thus to create better science. This is not the same as saying words have different meanings depending on when and where they are used. Instead, the aim is to define those meanings in a way that is intelligible to other scientists, and machine readable in the semantic sense. The Web Ontology Language (OWL) and Resource Description Framework in Attributes (RDFa) both rely on the work of human beings to generate the controlled vocabularies necessary for machine reading—it is only through working together that a true transdisciplinary understanding may emerge. Unlike collaboration or simple cross-disciplinarity, this work aims to be profoundly interdisciplinary—where the participants, working together, put themselves in the disciplinary contexts of the other, rather than a basic collaboration which would not yield as transformative a result. It is only through interdisciplinary work "integrating knowledge and methods from different disciplines, using a real synthesis of approaches" (Jensenius 2012) that the stated ERA goals may be achieved: "To explore and exploit new types of problem-driven and user-oriented research programs that go way beyond well-established modes . . . . To stimulate disruptive innovations to accelerate value creation" (Allmendinger 2015, 4) in the cultural heritage domain and beyond.

Chapter 2

FROM A BURIED FRAGMENT TO THE VIRTUAL ARTEFACT: A CASE STUDY OF GREEK POTTERY

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ABSTRACT

The fragmentary condition of objects is often an issue in the study of material cultural heritage. In archaeology, and in pottery studies in particular, the fragmentary condition of excavated objects impacts on research into their history and presentation. Ceramic vessels and vase fragments are the most numerous archaeological findings and a primary source of information about various aspects of ancient life: private, public, religious, economic and technological, social and artistic. The subject of this chapter is a fragmentary clay drinking cup, kantharos, a vessel attributed to the god Dionysus and a typical drinking vase used at symposia (gatherings). This particular kantharos was unearthed during the excavations at the ancient settlement of Therme, today's Karabournaki near Thessaloniki, Greece. The vase dates to the Archaic period between the seventh and the sixth century BC.

Although the kantharos is preserved to a large extent, its fragmentary condition challenges complete reconstruction. Evidence for reliable reconstruction is insufficient: the lower part that would originally have consisted of a base and foot, is missing. The process of virtual reconstruction through 3D visualization, described in this chapter, has contributed significantly to the study and presentation of the vase. The authors consider the advantages and limitations of technologies used. The process of creating this particular computer model may be applied to other fragmentary vases that come either from the excavation at Karabournaki or any other archaeological site or collection. This research may be of interest to experts in 3D technologies, as well as archaeologists and art historians, both academic scholars and students, museum curators and conservators, educators and other multidisciplinary audiences.

Keywords: Greek pottery, kantharoi, fragmented objects, archaeological excavation data, virtual reassembly, 3D approximation, visualization, COSCH

Introduction

The focus of this chapter is on how completion of pottery sherds through three-dimensional (3D) digital visualization contributes to archaeological research. Pottery is usually discovered in fragments and in vast numbers. Displayed in museums or deposited in storerooms, the clay sherds play an essential role in reconstructing the past. They are primary sources of information about various aspects of ancient life: private, public, and religious; economic and technological; social and artistic. They are, indirectly, also essential in archaeology for establishing the chronology of the finds under investigation (Biers 1992). For this reason pottery studies are a principal area of archaeological expertise (Orton and Hughes 2013).

It is commonplace, when unearthing pottery, to bring to light vases in a fragmented state. Problems and questions therefore arise as to the study, publication, and exhibition of pottery, especially in light of the vast quantities of excavated sherds (Sparkes 1996).

The application of 3D digitization methodologies to clay sherds can offer significant assistance in dealing with these matters, while the data produced are useful for enhancing archaeological research practice (Tsiafaki and Michailidou 2015; Koutsoudis et al. 2015; Koutsoudis et al. 2009). We discuss the challenges of pottery studies that require the collaboration of different disciplines, including 3D digitization, computer vision, pattern recognition, and computer graphics technologies. The chapter unfolds around a fragmented kantharos (drinking vessel) that has been unearthed in the ancient settlement of Therme, today's Karabournaki in northern Greece. Archaeological and museological questions articulated by scholars studying the vessel are presented and they guided all the stages of research, from the excavation of sherds, through their 3D digitization, to virtual reassembly and completion. The requirements of creating 3D computer models of sherds (in terms of materials, shape, hardware, software etc.) that are necessary for ensuring the adequate quality of data are also considered. To complete 3D digital replicas of the sherds targetless photogrammetric techniques, such as Structure from Motion and Multiple View Stereovision, were applied. The *London Charter for the Computer-based Visualisation of Cultural Heritage* (London Charter 2009) and the *International Principles of Virtual Archaeology* (Seville Principles 2011) were consulted for guidance.

Earlier Research

The application of 3D digitization technologies is considered a common practice in many areas of cultural heritage studies. In archaeology digitization is applied to big excavations and smaller projects (Remondino and Campana 2014). Both

Figure 2.1. Aerial view of the ancient site of Therme, today's Karabournaki near Thessaloniki, Greece. Photo: Karabournaki excavation photo archive, 1996.

archaeological research and its communication to the public are being enhanced by the data produced by such methodologies (Tsiafaki and Michailidou 2015).

For decades research efforts focused on establishing efficient and affordable methods for making 3D digital replicas. Some of these have been applied to pottery studies. The selection of a 3D digitization method depends on budget restrictions, the requirement of high-quality data in terms of geometrical and colour accuracy, as well as safe and efficient procedures of data collection (Breuckmann et al. 2013). Museums and archaeological organizations prioritized the creation of digital 3D repositories of their collections and thus databases with 3D content have become extremely popular. The 3D vase museum of the Perseus Digital Library is a relevant example (Shiaw et al. 2004). High-quality 3D digital replicas of vases enhance documentation (especially typology) and preservation procedures. They enable novel management methods and the remote study over the World Wide Web, simultaneously by a number of users. This is especially useful for studying sherds in storerooms. Restoration procedures, both virtual and actual (through 3D printing technologies) are assisted by the application of 3D shape processing and analysis. Digital 3D replicas play an important role in displays, as well as education and promotion, when used in a virtual museum or in a multimedia educational application.

Basic 3D technologies may generally support research into ancient pottery through:

- visualization of a vase, or fragment, by either range-based or image-based techniques (Willis 2011);
- estimation of a model's volumetric information (Mara and Portl 2012);
- digital reassembly of sherds (Tal 2014);
- an attempt to automatically classify vase types (Koutsoudis et al. 2010; Gregor et al. 2015);
- extraction of vase sections and drawings from 3D models (Hörr et al. 2011);
- digital restoration of fragmented or damaged vases (Hermon et al. 2012);
- use of the digital model in databases or virtual environments (Tucci et al. 2011).

Relevant applications of digital technology may range from image-based or range-based recording to virtual 3D modelling. A variety of hardware (less or more complex) and software (commercial or open source) may be used, ranging widely in cost. A 3D digital model may be produced in various formats and sizes, for a range of digital platforms, to be used by diverse users for different purposes.

Recent image-based methodologies offer the option of the digital 3D reconstruction of an object by narrowing the hardware requirements down to a digital camera and a computer system. The Structure from Motion combined with Multiple View Stereovision (SfM-MVS) has become an attractive and popular method. The literature confirms that the photogrammetry community considers this development as significant. SfM is defined as a pipeline of algorithms that are combined in order to create a 3D digital model of a static object, depicted in a set of unordered images, taken from different positions, scales and under varying illumination conditions. Researchers have assessed the quality of the SfM-MVS in relation to its cost, data collection procedures and quality, processing times, as well as human resources and specialist knowledge required. As with any other digitization method, SfM-MVS has its limitations. Nonetheless, a wide range of published results have proved that its applications to the cultural heritage domain are vital.

The authors discussed some aspects of the present study in a conference paper which appeared in the *Virtual Archaeology Review* (Tsiafaki et al. 2016).

COSCH Case Study of Greek Pottery: Description of work

Overview

The virtual reconstruction of the aforementioned kantharos was undertaken as one of the case studies conducted by the Colour and Space in Cultural Heritage (COSCH) network. A primary objective was the interdisciplinary approach to the study in order to contribute to a better interpretation and understanding of this cultural asset.

The Unearthed Fragments

The fragmentary kantharos (drinking cup) was unearthed during the excavations at the settlement of Karabournaki, seen in figure 2.1 (Tiverios et al. 2003a, 2003b). Its archaeological examination looked at (a) the shape of the vase and its typology; (b) the dimensions and state of preservation; (c) the dating of the vase; (d) the clay composition and the production techniques; (e) the decoration, painted or other; (f) the origin and attribution to a workshop; (g) the attributions to a potter and painter; (h) the original and subsequent uses, and (i) the location and context in which it was found.

These research questions are common to an archaeological study of any vase. From an archaeologist's point of view, pottery studies rely on frequent physical handling of the object (vase or sherds) which is necessary to study and fully document it through text, measurements, drawings, analytical results, etc. The sherds may be numerous, not adjacent, and cannot always provide sufficient information for a single and certain 2D reconstruction of the whole vase. Sherds are usually located in remote storerooms. From a museum professional's point of view, a vase or a sherd is one of the thousands found in museum storerooms. Pottery is documented, studied, conserved, and stored there. The conservator examines the museum piece, tries to prevent further damage, and occasionally restores the fragment (Georgaki 2012). If a pottery piece is chosen by curators for display in an exhibition, it means it contributes to the narrative of the show. Archaeological museums display coarseware and fineware, whole vases or sherds. The curators, like archaeologists, believe that pottery conveys important information about a culture of the past. They let the public, whether learned or lay, discover the object through its proper placement, explanatory texts, images, etc. Museum professionals, however, cannot be certain what the visitors, and particularly non-specialists, understand in the end (Einarsson 2014).

The clay fragments of the kantharos vessel (fig. 2.2) found at Karabournaki were studied in its archaeological context. The settlement was established in the late Bronze Age and was still active in the Roman times. Based on the archaeological data, the site flourished during the Geometric (ninth–eighth century BC) and, in particular, Archaic (seventh–sixth century BC) periods. A habitation area on top of a low mound, a cemetery at the foot of this mound, next to a harbour, are what remain of the ancient site (Tiverios et al. 2003a; Tsiafakis 2010). Its military significance and importance for trade was due to its location at the edge of a promontory in the centre of the Thermaic Gulf. The unearthed pottery and other findings came from well-known ancient workshops. This provides further evidence of the importance and far-reaching interaction of Therme (Tsiafakis 2010; Manakidou 2010).

Figure 2.2.
The fragmentary Karabournaki kantharos. Photo: Karabournaki excavation photo archive, 2010.

The vase dates to the Archaic period. It was found amongst the settlement's architectural remains. Kantharos was a popular shape in ancient Greece (Courbin 1953; Villard 1962; Kilinski 2005) especially in Macedonia and Thrace. However, this particular vessel appears to be unique in terms of its profile and its decoration. The primary characteristic of its decoration are four snakes, made from separate pieces of clay, added to the upper part of the vase. The snakes surround the body of the kantharos, with their heads facing the inside of the rim, as if they were about to drink from the vessel. Kantharos is known as a vase of the god Dionysus. It was a typical drinking vessel at symposia, or social gatherings with food and drink. However, this decoration suggests a ritual vase, leading to a hypothesis that might offer significant insights into life in the area. Although the vase presents some similarities to the G 2-3 ware (Ilieva 2013), it cannot satisfactorily be attributed to a particular workshop. Comprehensive findings of archaeological research into the vase will be a subject of an independent study.

From a museological point of view, the fragmentary condition of the vase is a major concern. From the collection management perspective and the responsibility for the preservation of objects for future generations, a fragmentary ceramic requires special care.

In order to fulfil its commitment to education, study, and enjoyment, the museum should present the kantharos alongside information that enables the public to understand its original form and use. Learning activities and interpretative displays of tentative reconstruction and plausible restoration (in 2D or 3D, or both) serve as a means to this end.

Creating the Virtual Artefact

Many original fragments of the Karabournaki kantharos have survived. The lower part is missing, which makes the virtual completion of the vessel particularly difficult. The digitization of the sherds in 3D, their virtual reassembly and the completion of missing parts were informed by archaeological evidence and museological practice. Various types of kantharoi were studied by comparison in order to understand the generic shape (Tiverios 1996). The archaeological reconstruction of the upper parts of the vase involved joining fragments. The archaeologists came up with a tentative initial shape.

The creation of the virtual artefact was carried out in two stages: the digitization of the sherds, and the virtual reassembly including 3D approximation of the missing parts. The data set acquired through digitization was used in the second stage. The use of the term "approximation" should be noted. It clarifies that the 3D reconstruction of the complete vessel is an attempt to approximate it. An accurate, full reconstruction is not possible without information about the missing parts.

3D Digitization of the Sherds

The SfM-MVS method was selected for the 3D digitization of the sherds as suitable for dealing with the colours and richness of features on the sherds' surfaces. The choice of this specific method was further justified by the efficiency of the data collection, in relation to the number of sherds, as well as the time restrictions of this project and the team's previous experience of SfM-MVS applications.

A commercial implementation of the SfM-MVS was selected. Agisoft's PhotoScan Professional has been used by the same research team on various digitization experiments that indicated that the tool can be used for photogrammetry projects (Koutsoudis et al. 2015; Koutsoudis et al. 2014; Koutsoudis et al. 2013). For the data collection phase, a pair of mirrorless DSLR cameras (Samsung NX1000) equipped with CMOS sensor (size: 23.5 × 15.7mm, effective resolution: 20.3 mega-pixels out of 21.6 mega-pixels, pixel pitch: 4.26 μm) were used. The lenses used were 20–50 mm along with 40.5 mm circular polarizing filters. A set of two Elinchrom Mini A studio lights (5500° K), with hooded diffuser softboxes that control light scatter and prevent lens flare, were also used. In order to minimize time and speed up automation of data collection, a computer controlled turntable (Kaidan Magellan Desktop Turntable MDT-19) and a relay-based USB controller for triggering the cameras from distance were used. The cameras were fixed on tripods. An in-house-developed software tool controlled both the turntable's rotation step and the cameras' triggering. This approach allowed the automated generation of closed-loop image sequences and at the same time eliminated any image blurring. The aperture, exposure, white balance, etc., on both cameras, were set manually in

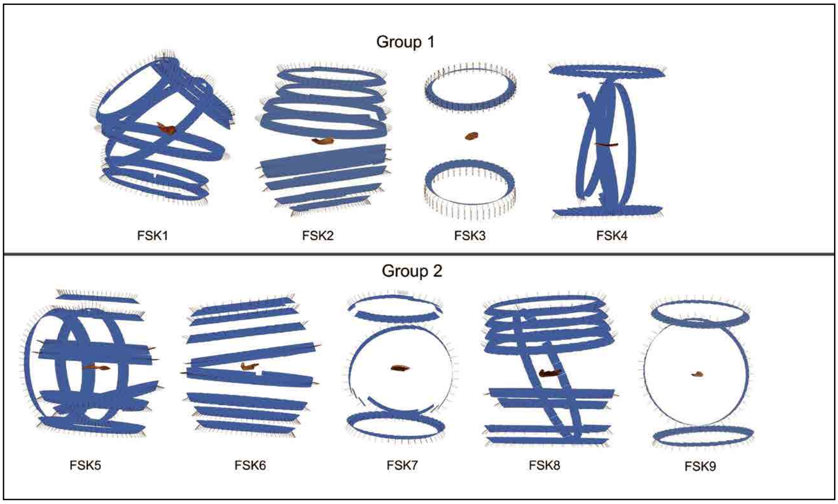

Figure 2.3. Viewpoint spatial distribution of sherds during photoshooting. © Athena Research Center, Xanthi, 2016.

order to achieve the deepest possible focused field-of-view and a uniform colour sampling for all images. More specifically, white balance was performed manually using ImageWare's colour scanner test target (S2N CSTT-1a) and it was kept constant throughout the data collection phase. However, colour variations (in the visible spectrum) between the fragments are still visible due to variable forms of erosion. An average colour value variance of 5.04% (three primary colour coefficients Red 4.47%, Green 5.65%, Blue 5.01%) was observed between the actual images and the texture maps that measure a total of 76,303 unique colours. These values were calculated on each one of the sherds by averaging the values in areas of 5 × 5 pixels and then compared with similar areas on the actual images.

This semi-automated data collection approach minimized the times a sherd had to be handled. Nevertheless, the repositioning of the digitization equipment for almost every sherd was unavoidable as a similar 3D reconstruction quality was required, in terms of point cloud density and ground sampling distance. The sherds were organized into two groups, based on information provided by the archaeologists. Group 1 consisted of four sherds (FSK1–FSK4) while Group 2 was composed of five (FSK5–FSK9). The grouping was based on the sherds' connectivity. It should be noted that some of the larger sherds (e.g., FSK1, FSK2, and FSK5) were composed of smaller ones that had already been glued together by the conservators and scanned as a single piece.

Figure 2.3 shows the viewpoints in spatial distribution, used to capture each sherd. The number of image sequences corresponds to the geometrical-morpho-

Figure 2.4. Visualization of 3D digital replicas of sherds using Vertex Paint and Smooth Normal Shading visualization approaches. © Athena Research Center, Xanthi, 2016.

logical complexity and size of each sherd. Thus, the more complex the sherd, the more images were required for its complete digitization. A large number of image sequences guaranteed that a 3D reconstruction was solved by the software combining all images into a single network. It is important to avoid partial-scan alignment procedures as they are based on error-minimizing approaches and reduce the geometrical accuracy of the digital replica.

Nine sherds of varying dimensions were reconstructed (fig. 2.4) from 3571 images. Such a number might be considered large. Given the fact that access to the sherds was limited and an accurate 3D reconstruction without partial scan alignment was a prerequisite, this number of images should be considered valid. Detailed information about each digital replica can be found in Table 2.1. The average ground sample distance was 36.73 μm. This level of accuracy is normally required for professional recording of material cultural heritage. For this project, such a resolution might be excessive. Given the fact that the digitization team had one-time access to the sherds, a high resolution was considered best practice. A fixed pixel size (equal distance between the cameras' sensors and the surface of the object) was impossible to achieve. This is depicted as a variance in ground sampling distances (GSDs) and in the average distance between consecutive vertices (considered as high accuracy) of the digital replicas' 3D point cloud (Table 2.1). It should be noted that the total number of images being used (2851) was lower than the total number of images that have been captured (3571). The complete 3D reconstruction of the sherds would have been possible with fewer images. However, as mentioned, access to the sherds was restricted and thus the digitization team worked in a way that enough data were collected and hence additional image sequences were captured.

Virtual Reassembly and 3D Approximation of Missing Parts

A manually implemented pipeline was followed to perform the sherds' virtual reassembly and an approximation of the vessel's missing parts. The pipeline involved the following steps: (1) axis of symmetry detection, (2) spatial distribution and alignment of the two sherds groups based on the axis of symmetry, (3) missing parts generation by using the available data and 3D mesh processing techniques (lathe, 3D mesh Boolean operations and mirroring, etc.), (4) realistic visualization of the vessel using synthetic material (clay) for the approximated parts. The latter were implemented using Matlab and Blender software tools.

The largest sherds were considered best suited for shape analysis and information extraction. The detection of the axis of symmetry was a prerequisite for aligning the scattered sherds within 3D space and an important parameter for the approximation of the missing parts. Using Blender, several *plane-to-3D mesh* intersections were computed. The horizontal and vertical intersections were calculated on the least damaged areas of the selected sherds (FSK2, FSK5) in an attempt to extract the most accurate data. The resulting point sets lay on horizontal and vertical planes and describe different parts of the sherds' profile (fig. 2.5). The point

Table 2.1. Data collection details of each 3D digital replica sherd.

Sherd name	Number of images used for the 3D reconstruction	Ground sample distance (μm)	Number of image closed loops	Number of vertices	Average distance between two consecutive vertices
GROUP 1 – FSK 1	437	47.16	7	5,956,000	~110 μm
GROUP 1 – FSK 2	547	48.54	9	7,827,421	~82 μm
GROUP 1 – FSK 3	94	32.84	2	1,716,631	~55 μm
GROUP 1 – FSK 4	209	31.34	4	2,204,425	~50 μm
GROUP 2 – FSK 5	526	39.92	9	6,908,370	~80 μm
GROUP 2 – FSK 6	414	27.28	8	3,996,016	~48 μm
GROUP 2 – FSK 7	150	30.38	3	3,220,855	~61 μm
GROUP 2 – FSK 8	333	36.16	9	5,335,942	~70 μm
GROUP 2 – FSK 9	141	37.02	3	2,401,313	~57 μm
Totals / Averages	**2,851 / –**	**– / 36.73μm**	**– / 6**	**39,566,973 / –**	**– / 68 μm**

sets coordinates of the horizontal intersections were processed in Matlab and by using the best-circle fit function a range of circle equations were identified. These equations define the averaged interior and exterior boundaries of the vessel's main body. Additionally, the projections of the normal vectors of the facets that belong to the horizontal intersections were used to identify the axis of symmetry. The detection of a mathematically expressed unique axis was impossible. This was due to the fact that a vessel made by a human hand, although on the potter's wheel, could

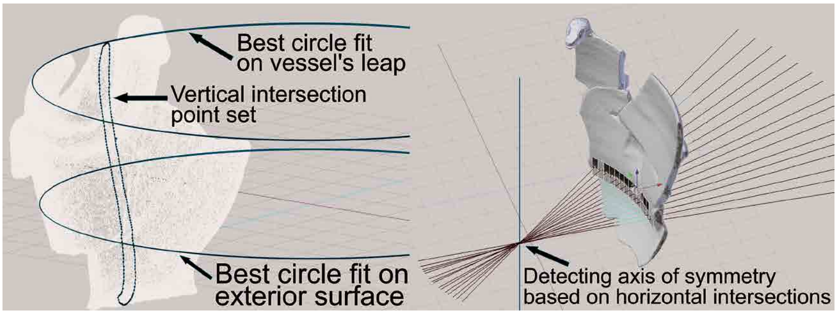

Figure 2.5. Extracting profile data using horizontal and vertical intersections of a sherd. © Athena Research Center, Xanthi, 2016.

not be symmetrically perfect. Furthermore, this was also an indication that sherds have been abstractly deformed through the centuries. Nevertheless, the averaged normal vectors intersection point's coordinates of the facets were calculated in Matlab and used to detect an optimum axis of symmetry (fig. 2.5).

The axis of symmetry was then used to position and align the sherds in 3D space. The connectivity between the different sherds of each group was provided by the archaeologists and performed within Blender. Colour information from the sherds' surface and various 3D modelling tools provided by Blender proved to be very useful for the manual alignment of the sherds. More specifically, the vertex-based snapping tool provided a means of detecting collision between the 3D digital replicas. It should be noted that when aligning partial scans with overlapping areas there are algorithms (e.g., ICP) that take under consideration both surface and colour information. In this case, this was not applicable as there were no overlapping parts between the sherds. The digitization team used the colour

Figure 2.6. The nine sherds aligned and organized into two groups. Spatial distribution of Group 1 sherds (left) and Group 2 sherds (right). Colour encoding indicates a different sherd. © Athena Research Center, Xanthi, 2016.

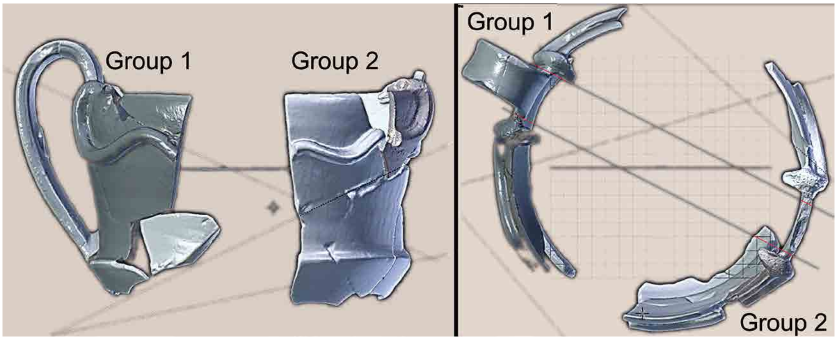

Figure 2.7. Spatial alignment of the two groups of sherds. Positioning of the two groups around the axis of symmetry (left). Position refinement using handle positions as reference (right). © Athena Research Center, Xanthi, 2016.

and decoration information provided for reference only. Blender software does not provide computer supported alignment mechanisms of partial scans. Once the two groups were completed (fig. 2.6) they were positioned into 3D space according to the interior and exterior limits introduced by the previously computed interior and exterior boundaries. They were then rotated around the axis of symmetry in order to be placed one opposite the other (fig. 2.7). This was based on the assumed symmetric positioning of the handles. Again, the alignment was performed manually within Blender. The process required an experienced user

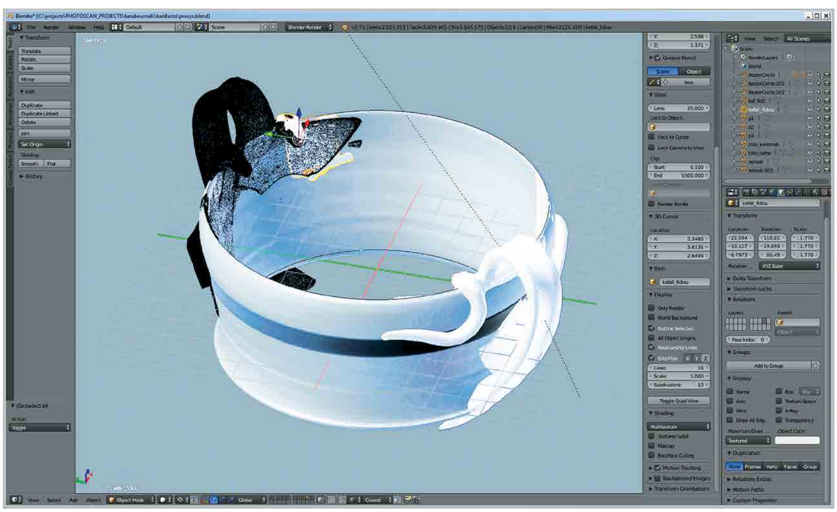

Figure 2.8. Using lathe to create an approximation of the vessel's main body. © Athena Research Center, Xanthi, 2016.

Figure 2.9. Visualization of the approximated body, with and without the sherds digitized in 3D, after applying the Boolean 3D mesh operations. © Athena Research Center, Xanthi, 2016.

Figure 2.10. Different viewpoint renderings of the virtually reconstructed kantharos. © Athena Research Center, Xanthi, 2016.

with a good understanding of a range of operations related to 3D rotation around a given centre of rotation and translation.

The 3D lathe technique was used to create the vessel's main body (fig. 2.8). The vase's body was composed by rotated instances of the vertical intersection point set in a 3D Cartesian coordinate system. As the 2D point set is rotated about a coplanar axis, an azimuthal symmetry is achieved. A vertical intersection point set representing the maximum available profile, was used to form the approximated body. The complete profile of the vessel could not be extracted from the available sherds. The vessel's base was missing and thus its approximation was based on design principles found in the literature. The archaeologists' contribution was of great importance for agreeing on a highly plausible base. Moreover and in order to provide a complete virtual vase, we performed the duplication and mirroring of the existing handle in order to produce the missing one (fig. 2.9).

Furthermore, a number of 3D mesh Boolean operations were performed between the synthetically reconstructed body and the digitized sherds. This resulted in a 3D mesh-based approximated representation of the vessel's missing parts (fig. 2.9). The final step was the generation of photorealistic visualizations of the vessel. Digital clay material was selected because it provided clean visual lines between the digitized and synthetic parts of the kantharos (fig. 2.10). The 3D technology was therefore used here in order to contribute to the pottery study, along with a desire to comply with the London Charter and the Seville Principles of visual transparency in historic visualization.

Critical Discussion and Evaluation of the Research

The choices made helped to achieve the principal aims, namely to assist with the archaeological study of the vessel, as well as to provide means for the communication of a fragmented vase to the general public.

Most importantly, both the expert pottery excavator and the 3D technology expert played leading roles within the 3D digitization and reconstruction team. They ensured that all the available research sources (pottery and archaeological data) and the latest advances in 3D technologies and techniques were taken into consideration.

The documentation of the case study, at all its stages, was thorough enough to clearly convey to all potential users its aims, methodology, and output. The commitment to include this work in the forthcoming website, newly designed for the Karabournaki excavation, will ensure the sustainable dissemination of information, including all the parameters of the 3D digitization and reconstruction of the kantharos, to the public.

Digital preservation of the computer-based visualization data has been secured through rigorous digital archiving. A 3D model of the reconstructed vase will be printed, in order to create a physical 3D record of the work. Archaeological work may be aided by placing the extant fragments on top of the reconstruction. The excavators, working in academic and research institutions, will disseminate the work and its outputs in presentations and educational sessions.

Following the completion of the work an evaluation took place to examine the approach adopted for the study and its results. A group of COSCH members, among others, viewed and examined the 3D model. They were primarily archaeologists, museologists, and technology experts. They were already familiar with the study and had been kept informed on its progress through presentations given at COSCH meetings. All of them were present at the final presentation of the case study, raised various issues, and asked relevant questions. Their comments were recorded in a structured questionnaire consisting of six closed questions concerning (1) the adopted methodology, (2) the study's outputs, (3) the digitization approach, (4) the procedures followed, (5) the contribution to archaeology and museology, and (6) the communication of the vase to the public. At the end, any additional comment was recorded in an open-ended question.

The evaluation offered ideas regarding the 3D model and its use within the archaeological and museological fields, for both expert researchers and the general public. The appropriateness of the methodology undertaken and the relevance to the stakeholders' requirements was highlighted by all participants. They judged that the 3D model offered a significant improvement on the traditional graphic archaeological documentation system, since it provides high image quality and a digital copy of the vessel in real dimensions. It was noted that the model strongly contributes to the digital preservation of the material characteristics of the vase and is especially useful in the field of digital visualization.

The need for 3D models to become even more effective research tools was also stressed. This work on a unique type of vase—fragmentary and with specific features—was considered a base for further research. For example, the use of automatic methods could be considered in collaboration with other relevant projects. Manual processing should be avoided, as much as possible, to reduce the time and cost of such work. Automation could be applied to the reconstruction and creation of sections and other views of the vessel. Generally, the need to study the feasibility of the whole process, from a material and financial point of view, was underlined.

All the evaluators considered the 3D computer model a surrogate for the real artefact, that is, an authentic find that should be promoted alongside the archaeological knowledge that it represents. This knowledge could be better communicated through the addition of digital storytelling (Roussou et al. 2015).

From an aesthetic as well as technical points of view, the reconstruction of the original colours of the vase would help to create a visually more attractive 3D model. The application of SfM-MVS to 3D digitization proved adequate for the generation of high-quality 3D data. The semi-automated procedure enabled the generation of 3D digital replicas without the need to apply partial scan alignment procedures. The digitized sherds were aligned into groups with the help of 3D modelling tools available in Blender. The vertex-based mesh snapping is such an example. The produced virtual reconstruction is visually adequate but the exploitation of an algorithm that is able to quantify the matching error between two surfaces could be used along with the snapping tool, in order to achieve a more objective alignment of the sherds. From a more practical point of view, such accuracy would be more important for cases where matching surfaces are not degraded to such an extent or when the available sherds represent a larger proportion of the original object.

Future Research and Conclusion

The study of this unique vessel is of great importance to archaeologists. Its fragmentary condition set limitations to 3D reconstruction. Although an experienced archaeologist and a pottery specialist can recognize, classify, and date the pieces with ease, this is not always possible for less experienced researchers and the general public. Neither archaeologists nor the general public can have a complete picture of the kantharos in question, but its 3D model can assist in dealing with the research needs of both archaeology and museology. A 3D computer model can be made accessible whenever wanted, from everywhere, to be looked at from every side and as close as needed. The accurate 3D visualization can be used to study the shape and decoration of the vase. The model can provide a better sense of the vase than the 2D photos of individual sherds; while different versions of the 3D reconstruction model can assist with the restoration of the object without disturbing the fragments. The 3D model can be used in teaching about pottery, rituals, and in other courses. The excavation at Karabournaki is led by academics who are likely to benefit from this resource. A low-resolution model will be made available in the digital collection on the Karabournaki website for education.

A high-quality 3D model can be used in conservation to monitor the condition of the actual vessel, to assess any possible changes, and assist in taking decisions concerning its preservation. The model and the hypothetical reconstruction can be used by a museum for remote study, in virtual exhibitions (and also at their planning stages). It can be displayed next to the real artefact in an actual exhibition space, to allow the public to get a better sense of the ancient vase. To increase the realism, texture mapping can be applied to the approximated parts of the vessels, using the available sherds as the primary source of the colour information. It will take time for the actual vase to be thoroughly studied and exhibited. While it is kept in a storeroom, awaiting its full archaeological publication, this virtual demonstration may be very important. In an actual future exhibition space a 3D-printed base may be used to hold the actual sherds. Thus, the 3D model, digital or printed, will contribute to the enhancement of archaeological research and knowledge.

Chapter 3

BEYOND PHOTOGRAPHY: AN INTERDISCIPLINARY, EXPLORATORY CASE STUDY IN THE RECORDING AND EXAMINATION OF ROMAN SILVER COINS

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ABSTRACT

A study was undertaken by an interdisciplinary group of COSCH researchers between 2014 and 2016, to record and examine silver coins believed to be ancient Roman in origin. The aim was to evaluate the suitability of various advanced, non-invasive optical and spectrometric techniques for analysing the physical characteristics and elemental composition of numismatic objects. In order to compare results, the same two silver coins were used throughout the study: two denarii portraying Empress Faustina I, wife of Antoninus Pius, believed to be posthumous deification issues of AD 141. The questions addressed included the characterization and authentication of test coins, as well as technical issues in the multimodal recording of material cultural heritage with metadata and paradata. The team investigated whether the methods chosen for this case study responded to the needs of numismatists, and whether they could feasibly be applied in museum practice, to support research and conservation of historic coins, and to enhance the documentation and dissemination of numismatic objects through heritage science.

Keywords: numismatic studies, Roman silver coins, examination, optical techniques, multimodal recording, COSCH

Background and Purpose of the Study

This chapter introduces an experimental study of two silver coins, believed to be ancient Roman, and discusses some of its interdisciplinary outcomes. We undertook to investigate, in collaboration with other international researchers, how historic coins are examined and documented, and what is the role of modern, non-invasive optical and spectrometric technologies in today's numismatic research and museum practice. The network Colour and Space in Cultural Heritage (COSCH) facilitated research contacts between experts representing a wide range of interdisciplinary interests and expertise in optical, metrological and imaging technologies and material sciences. Benefiting from this combined expertise and access to specialist equipment, at a level that is rarely available to museums, this case study was designed to explore which of the advanced technologies available to us could enhance numismatic research and conservation, and museum practice in general. Therefore, our main objectives were:

- to assess current research and documentation practice: how are historic coins in numismatic museum collections being examined and recorded, presented and disseminated in the 2010s? What is the role of digital methods?
- to apply a wide range of optical and spectrometric techniques to measure and examine, and present the test coins;
- to compare the results of different technologies applied for the same purpose, in particular to compare the geometric measurements achieved through several 3D techniques;
- to compare the results of the same technology achieved by different laboratories; to consider variations, if any, in the specification of instruments (hardware and software), their setups, and possible differences due to the human operation;
- to assess the level of expertise required and issues related to a multimodal approach;
- to consider solutions for the dissemination of resulting data and to identify further research.

The investigation was carried out between September 2014 and October 2016. A more comprehensive account and discussion can be found on the dedicated website at https://coschromancoins.wordpress.com. A core group of initial proposers was subsequently joined by other researchers to form an interdisciplinary team of twelve specialists, some with expertise in two or more disciplines, including: archaeology, art history and museology, conservation and heritage science, chemistry and electrochemistry, mechatronics and engineering metrology, computer science, computer graphics, and image processing. The work was monitored by a metal conservator and was peer-reviewed periodically by the COSCH community. Other relevant expertise was called upon throughout the study and is gratefully acknowledged (see p. xviii). We approached curators and conservators of various numismatic collections in order to assess their familiarity with the technologies applied to this study. We were interested to know, in museums we contacted, who was using the recording/examination/visualization methods in question to study and document coins, and how they were being used. It transpired that, apart from 2D digital photography, microscopy, and X-radiography, other specialist optical and spectrometric recording and examination technologies are applied only sporadically, typically through external collaboration, as part of a particular research or conservation project, or prior to an exhibition or loan of the object(s).

Early in the study we researched museum records, both published and unpublished, of the same type of denarius as used in our tests. We assessed the level of detail of information provided, concerning in particular the measurements, material, condition, past examination and treatment, and the quality of the visual records, if any. The records examined typically consisted of skeletal inventory information and identification, recent provenance, and two photographs (obverse and reverse), but sometimes the photographs were not included. Some collections have not yet been fully photographed and the basic documentation is prioritized above more advanced recording. Published museum records are affected (note, for example, the lack of images at www.getty.edu/art/collection/objects/19807/unknown-maker-denarius-with-faustina-the-elder-roman-after-141/; and www.britishmuseum.org/research/collection_online/collection_object_details.aspx?objectId=1468968&partId=1&searchText=Diva+Faustina&page=1, accessed 26 March 2017) although the lack of a visual record is sometimes due to copyright or other restrictions. Such standard museum object records are fundamental to research into the object, its long-term care, and dissemination. These are often too basic. We sought ways in which they could be enhanced, through better integration with conservation documentation and inclusion of more comprehensive scientific information and particularly within modern collection management systems.

Having subjected the coins to preliminary analytical, scanning and imaging tests, we faced a problem, common in interdisciplinary digital research: how to present technical solutions to potential users, given the lack of a shared approach and vocabulary to interrogate fully the specific needs within the relevant communities of heritage practice? Who would potentially benefit from the technologies available: the heritage scientists and conservators? The curators of numismatic collections and other subject specialists? Or perhaps the museum audience? What are the parameters they require?

Experts in Roman coinage and metal conservators were approached to advise and eventually to evaluate the methods used in the COSCH study, the resulting diverse records of the coins, and their potential benefits for numismatic practices.

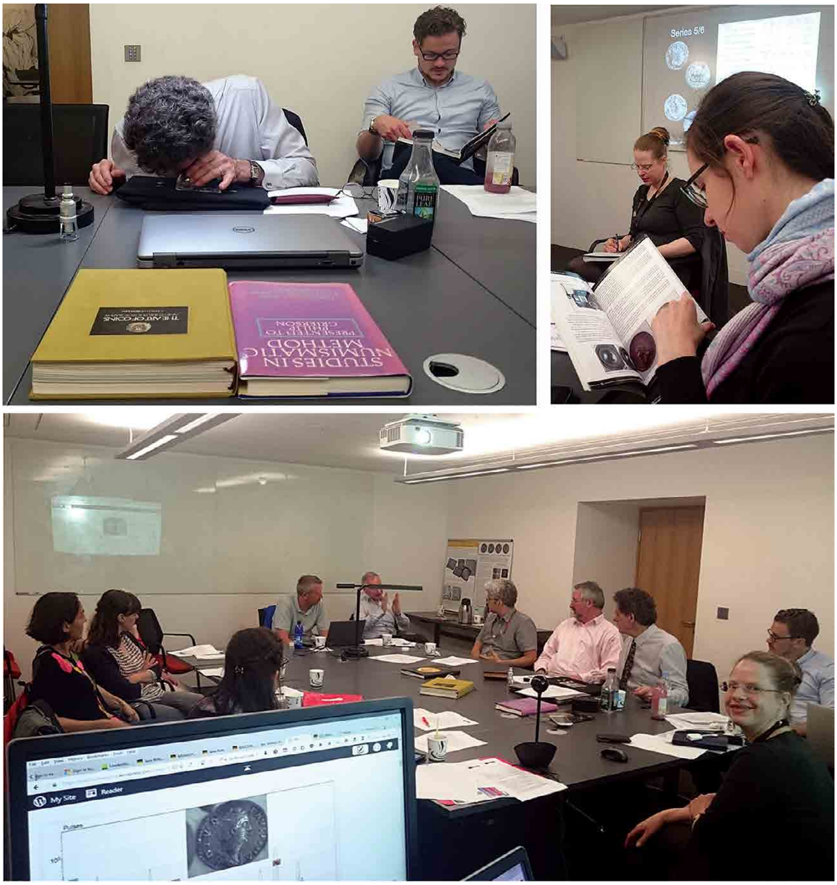


Figure 3.1. The COSCH "Day of the Denarius" held at University College London, 22 June 2016. Photos: A. Bentkowska-Kafel.

This ongoing communication culminated with a study day held at University College London on 22 June 2016. The leading experts in Roman coinage and metal conservators from British museums were invited to look at the denarii of Faustina the Elder used in this study, and to express opinions concerning their authenticity and significance. The experts and the COSCH scientists examined each coin through a magnifying glass (fig. 3.1). Expert opinions and descriptions of the current methods and processes in numismatic museum practice were presented and discussed. The proceedings, which were audio/video recorded, have informed the conclusions presented here. The senior archaeologist at the Museum of London Archaeology (MOLA), for example, deals with coins that come from this museum's own excavations. "They go to the conservation lab first, where they are all cleaned,

Figure 3.2. Numismatic display with a denarius of Faustina the Elder. J. Paul Getty Museum, Santa Monica, CA. Photo: A. Bentkowska-Kafel, 2016.

treated and X-rayed as well as record photographed. Then they come to me for identification, cataloguing and analysis. If I request it, more detailed studio photographs are taken—usually for publication" (communication 16 June 2016). Another numismatist mentioned scanning coins on a flat-bed scanner. The participating museum conservators, who routinely deal with historic coins, often found in hoards, explained that typical treatments involve removal of encrustation and cleaning. Also discussed were the environmental conditions required for storing coins and issues in their public display.

Earlier Research

Earlier historical, museological, scientific and technical research into numismatics was critically reviewed to inform our work. Methods of study, classification and documentation, and display or storage of historic coins have been developed over the centuries of collecting. The Hutten-Czapski Collection of the National Museum in Kraków, Poland, the institution of one of the co-authors, represents a historic model of a numismatic gallery, akin to the imperial Coin Cabinet of the Kunsthistorisches Museum, Vienna, but modernized to include public multimedia displays next to some glass cases with coins. Museum visits organized during

COSCH meetings, and independently, provided opportunities to discuss how numismatics are presented in museums, both *in situ* and online, and the solutions (or lack thereof) to the typically restricted viewing of both obverse and reverse of these small objects (fig. 3.2); and the low light levels when they are shown together with paper banknotes.

Some methods of studying numismatics and the associated major catalogues go back centuries and many remain standard. The chronological and geographical classification system of coins, for example, known as the *Eckhelsche Ordnung*, was introduced by Hilarius Eckhel in the eighteenth century and is still in use. Records of Roman coins invariably include references to the *Roman Imperial Coinage* (RIC) as a standard (Mattingly and Sydenham 1923–). The Online Coins of the Roman Empire (OCRE) relies on RIC's numbering system and includes every published record of coins from this period, of which half is illustrated. The coinage of Faustina the Elder (d. 140) is the subject of a monograph by Beckmann (2012). The author considers how the deification of this empress and her subsequent cult as Diva Faustina were manifested and commemorated in coins issued posthumously. A comprehensive study of this coinage, minted in Rome (at a site thought to have been just southeast of the Colosseum) at least until 160, and in the provinces, as well as of forgeries and hybrids, is provided by Beckmann, alongside a reconstruction of the production sequence through a study of the dies, minting methods, and materials. "*Denarii*, being much too abundant, were not part of the die study" (Beckmann 2012, 15). Modern numismatic scholarship relies on identification and comparison of dies; coins are still examined and compared by hand.

The use of modern digital technologies and analytical techniques has been explored, particularly in conservation science, as soon as they became available, resulting in a number of notable applications. The technical aspects of this study have been informed by earlier research, including: propositions for the development of relevant methods for recording historic coins in 3D, rather than 2D images, whilst addressing common issues relating to synchronous acquisition of geometric and colour information, and the problem of specularity of the metal surface (see Zambanini et al. 2009, for an overview); applications of Reflectance Transformation Imaging (RTI) to the study and presentation of numismatics were discussed by Mudge et al. (2005 and CHI 2012), some available for online viewing; since the 1990s the metallurgy of Roman silver coinage has been a subject of ongoing research led by Ponting and Butcher, more recently using optical and scanning electron microscopy (SEM-EDX) and other technologies (Ponting, Butcher et al. n.d.). Relevant research undertaken by Hoyo-Meléndez et al. (2015) included the elemental surface analysis of medieval coins, using X-ray fluorescence spectrometry (XRF), and showed the potential of this method for providing insights into the provenance of the raw material and manufacturing processes. A complete list of sources consulted by this study can be found at https://coschromancoins.wordpress.com/bibliography/. A considerable body of scientific literature offers many relevant solutions, particularly in the area of 3D data capture, including comparison of different scanning techniques, although applied to non-numismatic objects (Böhler 2006). However, no earlier research has been located which applied a comparable range of different optical and spectrometric techniques to the same objects, trying to contextualize the results within museum practice. The lack of an established methodology and compatible standards in multimodal acquisition; the processing and interpretation of heterogeneous data; and the presentation formats that would be accessible to non-scientists, were amongst the challenges for this experimental study.

COSCH Roman Coin Study: Description of Interdisciplinary Work

Test Coins

Historical, Social, and Artistic Significance

A small selection of historic silver coins was made available to this study, of which two different denarii portraying Faustina the Elder (coin A: RIC III Antoninus Pius 351a; coin B: RIC III 400; fig. 3.3) were used in all tests. The overall designs are similar, but the decoration and legends vary (see https://coschromancoins.wordpress.com/ for the 2D/3D visual records created). Each denarius shows a bust of Faustina in right profile and draped. The facial expression and elaborate hair style differ in each obverse, inscribed DIVA FAVSTINA along the perimeter. The reverse of one coin features the personification of Aeternitas, the other of Vesta, both as standing, draped figures, identifiable through the accompanying legend. The coins commemorate the deification of Faustina, by her grieving husband Antoninus Pius (*reg.* 138–161), in 141, also marked by the construction in the Roman Forum of a temple in her honour. Various types of the posthumous denarius of Faustina the Elder are known (RIC III). They vary in design and iconographical details.

Figure 3.3. The denarii of Faustina the Elder used in the COSCH study. Left: coin A (Aeternitas). Right: coin B (Vesta). The images were derived by image processing from sets of 64 images taken by a Nikon D200 camera with directional flash illumination. The effect simulates images of coins obtained by a photographic studio setup with axial illumination. © Lindsay MacDonald, 2017.

The legends change depending on the iconography. They can be found in many numismatic collections in Europe and North America.

How coins were minted in ancient Rome is known from textual sources and iconographic representations, *inter alia* in sculpture and medallions, depicting scenes with moneyers and their tools. A coin evidences the design of the die used to strike it, in negative, and a sharp eye can spot if two coins of the same design share one or both pairs of dies or even if two coins of different designs share the same obverse die suggesting a chronologically close production run. Coins may show tooling marks as a result of unscrupulous attempts to restore worn details or otherwise add value in the modern collecting trade. As hand-manufactured objects, production errors with dies can cause, for example, a shifted imprint owing to double striking; and like many archaeological objects their form can change with subsequent abrasion or even reuse over time.[1]

Legal and Ethical Questions

A number of ethical and legal questions have to be addressed when dealing with historic coins. The non-invasive and non-destructive nature of examination was paramount in this study. This is not always the case. In traditional metallographic work, "In order to prepare a coin for metallurgical examination a substantial section needs to be cut from the coin to expose a representative area of metal" (Butcher and Ponting 2015, 130). In a different study, involving bulk chemical methodology, "Samples for compositional analysis were removed from the 'heart-metal' of each coin by drilling" (Butcher and Ponting 2012, 557) to avoid the surface contamination. The latter invalidated an early application of XRF to measure the fineness (silver content) of Roman denarii, by D.R. Walker in the 1970s, which may serve as a cautionary example of relying on the wrong data. The fact that a powder or spray is applied to a metal object, to reduce its specularity, prior to its scanning with laser or structured light, is rarely mentioned. The residue is brushed off or removed with distilled water. The precision of measurements is affected although negligibly. We sought conservators' advice as to a possible negative impact on the coins. Details of the treatment have been recorded for each test, see https://coschromancoins.wordpress.com/test-coins/pre-test-treatment-of-coins/.

Counterfeiting, both ancient and modern, of historic coins is notorious, and hence the question of authenticity is key to any numismatic study. Material and contextual evidence are particularly important, but rarely unequivocal. Compaña

1 The authors acknowledge historical information kindly provided by Richard Abdy, Curator of Roman Coins at the British Museum, which has greatly enhanced the original version of this paragraph.

Prieto et al. (2014) proposed a combination of techniques for detecting counterfeit Roman coins. The physical and elemental analyses, alongside the comparative stylistic and iconographic interpretation were essential for authentication of the coins used in this study, and supported the opinion of expert numismatists. The coins used in the COSCH study were privately owned and were acquired on the British art market, probably in the 1980s. The denarii of Faustina the Elder continue to be widely available from numismatics dealers, valued at approx. 30 USD in 2015. Silver coinage was produced in Rome in larger volume than bronze and gold. Unless a denarius of Faustina the Elder displays a specific production fault or other rare features, it does not command a higher price. Questions were raised whether such historic objects, authentic or fake, can easily travel legally between laboratories located in different countries. Relevant national and international legislation for dealing with cultural objects was consulted, particularly the regulations concerning temporary movement and the general exemptions of many categories of numismatic objects up to a certain value.

Methods

The COSCH Action was set up with the aim to facilitate the use of optical measuring techniques in the documentation of European cultural heritage. The coin study followed this objective by applying, comparing (where relevant), and critically assessing a range of different optical and spectrometric techniques to examine and record the denarii, including X-ray microtomography (microCT), XRF, scanning electron microscopy coupled with energy-dispersive X-ray spectroscopy (SEM/EDX), photostacking, RTI/PTM, photogrammetry/Structure from Motion (SfM), laser and structured light scanning, photometric stereo, alongside the relevant visualization and dissemination methods. We attempted to find out how individual techniques can complement each other or be fused, and how the resulting data can be repurposed to support another test or a different application. For example, the study explored the use of XRF spectrometry and SEM/EDX as a complementary physico-chemical method to 2.5D and 3D documentation.

By consistently using the same coins in all tests, this study aimed to compare geometric results obtained with different spatial recording techniques, and also to assess how using different instruments and setups may affect the results within applications of the same technology. The results have been published at https://coschromancoins.wordpress.com.

We present here some scientific and methodological issues of such multimodal recording, and in particular of dealing with heterogeneous data. The development of an efficient and comprehensive methodological framework for the 3D digital data acquisition, processing, and analysis of historical silver coins (fig. 3.4) is fundamental

Table 3.1. Chronology of data acquisition systems and techniques used in the case study. © Vera Moitinho de Almeida, 2016.

Date	Institution	System/Technique	Cleaning	Coating
2014.09	WUT	3D Structured Light (SL) Scanning	Yes	Yes
2014.10–11	SAS	MicroCT	×	×
		SEM/EDX	Yes	×
2014.12	NMK	XRF	×	×
2015.01	AICON	3D SL Scanning	×	×
2015.01	RBINS	3D SL Scanning	×	×
		SfM	×	×
2015.02–03	UCL	3D Laser Scanning	×	×
		RTI/PTM	×	×
		Photometric Stereo	×	×
2015.04–05	CyI	3D Laser Scanning	×	×
		RTI/PTM	×	×
		XRF	×	×
2015.10	AICON	3D SL Scanning	Yes	Yes
2016.01	RBINS, UCL, US	3D SL Scanning	×	×
		SfM	×	×
		RTI/PTM	×	×
2016.06	ITAM	3D Laser Scanning	n/a	n/a
		Digital Microscopy	n/a	n/a
		RTI/PTM	n/a	n/a
		Photometric Stereo	n/a	n/a
		Pycnometry	n/a	n/a
		SEM-EDX	×	×

Participating institutions were: AICON – AICON 3D Systems GmbH, Germany; CyI – The Cyprus Institute, Cyprus; ITAM – Institute of Theoretical and Applied Mechanics, Academy of Sciences, Czech Republic; NMK – National Museum of Kraków, Poland; RBINS – Royal Belgian Museum of Natural Sciences, Belgium; UCL – University College London, UK; SAS – Slovak Academy of Sciences, Slovakia; US – University of Southampton, UK; WUT – Warsaw University of Technology, Poland.

Observations
Coating applied: Helling 3D Scanning Spray, Helling GmbH. TiO2 powder dispersed into an alcohol solvent. Applied with airbrush and compressor; removed mechanically with brush; cleaned with distilled water; dried with hot air. 3D models not included for further comparisons: computational artefact caused by systematic error during 3D data acquisition.
Data to be used as Ground Truth (GT): not made available in time.
Used isopropanol for ultrasonic cleaning the coins. Conservators from the British Museum were dubious about ultrasonic cleaning techniques.
–
3D data acquisition repeated 2015.10.
3D models: not representative of the possible highest resolution outcome of system.
–
3D models: obverse and reverse recorded separately, not aligned back to front. Not representative of the possible highest resolution outcome of system.
–
3D models derived from RTI/PTM and 3D laser scanning from UCL.
3D models not included for further comparisons: data quality too unreliable and low (see report).
–
–
Coin A: coating applied; removed with water. Coin B: no cleaning performed; no coating applied. 3D models: not representative of the possible highest resolution outcome of system. Used as reference data (system has values according to standard procedures for estimation of accuracy: VDI/VDE 2634).
3D models: not representative of the possible highest resolution outcome of system.
–
Images revealed changes in the reflectivity of the surface's material, possibly due to cleaning, whitening of TiO_2, handling, storage and/or metal oxidation.
3D models not made available in time. Obverse and reverse recorded separately.
–
–
3D models not made available in time.
Coins exposed to helium gas.
Elemental composition determined some contaminated points.

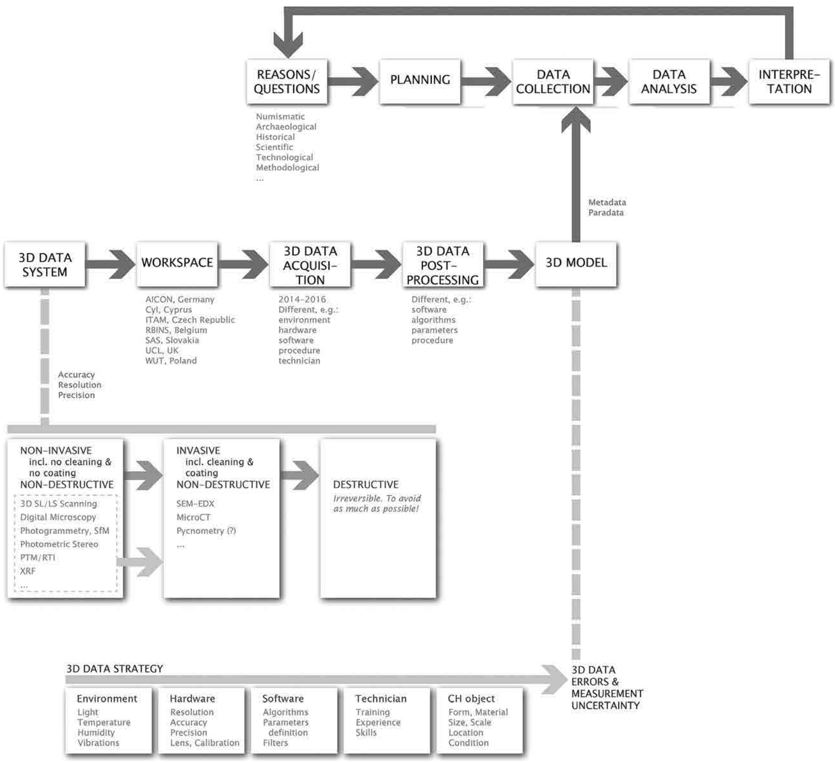


Figure 3.4. Proposed methodological framework for the 3D digital data acquisition, processing, and analysis of historical silver coins. © Vera Moitinho de Almeida, 2016

to a thorough understanding of how the workflow functions, since each stage of the process depends on the outcome of the previous stage(s) and determines the subsequent ones. However, the availability of particular partners at a particular time affected the logistics of passing the coins to different institutions and countries, and thus determined the order, type, and dates of data acquisition. Table 3.1 presents the chronology of data acquisition by different institutions participating in this case study.

Characterization of the Test Coins Resulting from Application of Different Techniques

RTI/PTM

The RTI technique depends on the acquisition of a set of images in pixel register, each image being illuminated from a different direction. Four data sets were acquired at different laboratories on different dates, using dome-based setups with different equipment, software, and data formats (table 3.2).

Table 3.2. Equipment and parameters of capture of the RTI domes. Participating institutions: CyI – The Cyprus Institute, Cyprus; RBINS – Royal Belgian Museum of Natural Sciences, Belgium; UCL – University College London, UK; US – University of Southampton, UK. © Aurore Mathys, 2016.

	UCL Dome (1)	CyI Dome (2)	RBINS Dome (3)	US Dome (4)
Date	March 2015	April–May 2015	February 2016	February 2016
Diameter	102 cm	60 cm	72 cm	100 cm
Number of lights	64	36	260	72 (76)
Light type	Flash	Halogen	LED	LED
Camera	Nikon D200	Canon EOS 5D Mark II	Allied Vision Prosilica GX 6600	Nikon D800E
Lens	Nikon AF Micro-Nikkor 200 mm f/4D ED-IF	Canon EF100 mm f/2.8 Macro USM	Nikon AF Micro-Nikkor 200 mm f/4D ED-IF	Nikon AF Micro-Nikkor 200 mm f/4D ED-IF
Exposure	1/60	1/25	1/4	1/4
Aperture	f/11	f/6.3	f/8	f/8
ISO	100	150	–	200
Resolution	10.2 Mp	21.1 Mp	28.8 Mp	36.3 Mp
Image size	3872 × 2592	5616 × 3744	6576 × 4384	7360 × 4912*
Output size	1430 × 1360	5616 × 3744	3976 × 4120	4260 × 3290
Software to create RTI	Custom (Matlab)	Train Brain	PLDDigitize	RTI Builder
White balance	Flash	Yes	Yes	Yes
Output format	.rti, .ptm	.ptm	.cun	.rti

* RTI builder cannot process images that large, so they have to be scaled down.

The tests revealed numerous differences between the data sets, making them difficult to compare. No comparison of the extracted normal vectors was possible, because of inconsistent placement of coins, which changed their orientation, and the use of different lenses with different magnifications and geometric distortion characteristics. Although subjective, the visual assessment showed that, despite all the captures being made with automatic white balance, the colour balance differs from one result to another (fig. 3.5). Analysis showed that these differences could not be explained by the varying capture parameters (ISO, aperture, exposure time), but must also be due to the spectrum of the illumination changes

Figure 3.5. Appearance of coin A obverse, detail: (a) RTI from dome 1; (b) RTI from dome 2; (c) RTI from dome 3, albedo mode; (d) RTI from dome 3, ambient mode; (e) RTI from dome 4; (f) focus stacked picture. © Aurore Mathys, 2016.

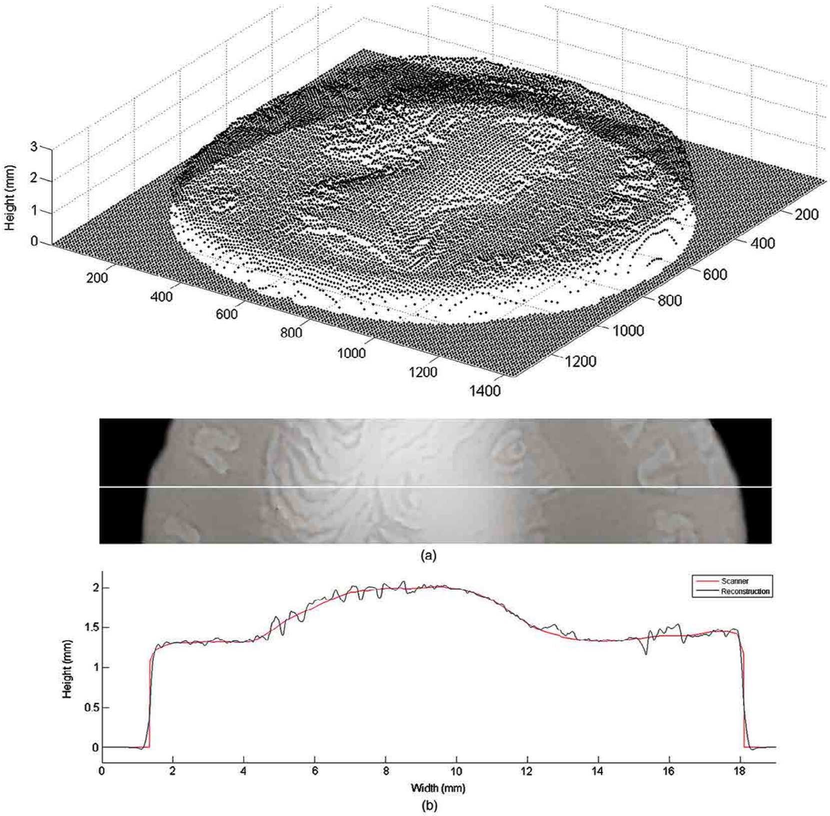
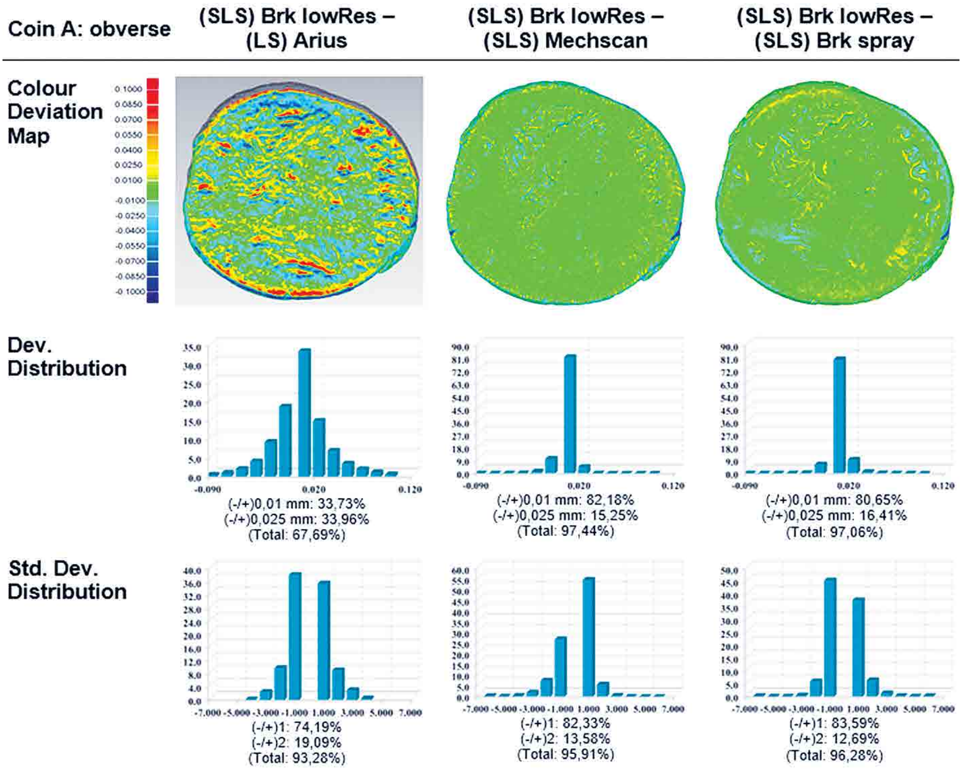


Figure 3.6. 3D reconstructed surface based on photometric stereo. Horizontal section with elevation showing (a) laser scanner height and (b) reconstruction. © Lindsay MacDonald et al., 2017.

over time and different processing methods. The specularity differed according to the illumination geometry, and also the visualization software. Overall realism, sharpness, surface texture, and other parameters also differed from one capture to the other. A significant factor determining the appearance of the RTI image is the handling of the tonal range in both acquisition and processing, such as the setting of white and black points, gamma correction, and contrast enhancement.

The comparison of the four systems also showed the limitations of the RTI technique. It should be applied to flat objects, where there is a well-defined planar surface with limited relief, otherwise the depth of field becomes an issue, especially when the item is small and the magnification large. RTI illumination domes are only suitable for small specimen sizes because automated "stitching" of images showing parts of the object is not possible. Not only should the whole



object fit within the image field of the selected lens, but also (in order to avoid distortion and excessive illumination gradients) the lens should not have too wide an angle of view at the fixed imaging distance. A guideline is that the diameter of the object should not exceed one third of the diameter of the dome. For small objects and large magnification the stability of the camera is a key factor in achieving a successful result. There should be no movement whatsoever of the camera relative to the object throughout the acquisition sequence.

3D Recording and Imaging

The following 3D data techniques were applied: Structure from Motion (SfM), laser scanning (LS), structured light scanning (SLS), and photometric stereo (PS), as shown in figure 3.6.

A summary of the various 3D data sets of the coins is presented in table 3.3. A more comprehensive description of the 3D data acquisition process and post-processing

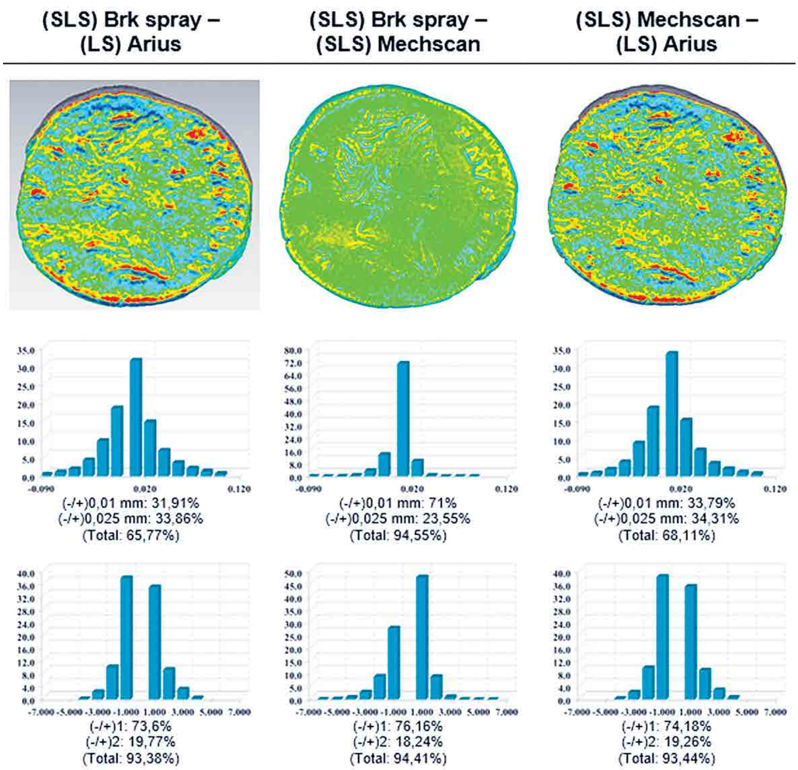


Figure 3.7. Results of the deviation between the obverse of the 3D models of coin A: colour deviation map, deviation distribution of points, and standard deviation of points. © Vera Moitinho de Almeida, 2016.

of the data, including metadata and paradata records, can be found in Moitinho de Almeida (2015), MacDonald et al. (2017) and on this case study's website.

The distinct 3D models acquired by different institutions, systems, techniques, methods, and procedures were compared. The purpose of the recording was to demonstrate the capabilities of each 3D technique applied, and its potential value for providing spatial and visual information for documentation of the object. For various reasons, the 3D models listed in table 3.3—(LS) Arius-rev, (LS) ITAM, (LS) NextEngine, (PS) ITAM, and (SLS) WUT—have not been included in the analysis. The major drawback of the approach adopted for the comparison of spatial data was the failure of the acquisition that was expected to provide the "ground truth" data against which other data sets should have been compared. Consequently, (SLS) Smartscan was chosen as reference data set, as Smartscan systems are calibrated according to standard procedures for estimation of accuracy (VDI/VDE 2634 2012a, 2012b).

Freeware, open source, and commercial metrology software packages—CloudCompare (danielgm.net), Geomagic Control (3D Systems), Meshlab (Visual

Table 3.3. 3D data sets, systems, and techniques used.
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Coin	3D model	Survey institution	3D data acquisition system type	3D data acquisition software
A, B	(LS) Arius-obv/rev*	3DIMPact, UCL	Multi-stripe Colour Laser Scanner	A3D (Arius-Technology)
	(LS) ITAM*	ITAM	Laser Scanner	n/a
	(LS) NextEngine	STARC, CyI	Multi-stripe Laser Scanner	ScanStudio HD 1.3.2 (NextEngine)
	(mCT) SAS	SAS	MicroCT	n/a
	(PS) ITAM*	ITAM	Photometric Stereo	n/a
	(PS) Ls-Ptm	3DIMPact, UCL	Photometric Stereo	Matlab
	(SfM) Canon	RBINS	Structure from Motion	n/a
	(SLS) Mechscan	RBINS	Structured Light Scanner	FlexScan3D
	(SLS) Smartscan	AICON 3D	Structured Light Scanner	OPTOCAT 2015R2
	(SLS) WUT	WUT	Structured Light Scanner	n/a

* Obverse and reverse recorded separately.

** Lateral resolution value for the lateral expansion (X × Y) in the centre of the measuring volume, according to the manufacturer/partner.

Computing Lab, ISTI-CNR), and Polyworks (InnovMetric Software)—were used to compute basic topological (table 3.4) and geometric (table 3.5) measurements of each 3D model, as well as for alignment and comparison between 3D models. The tested software did not calculate equally all geometric data, and the distinct 3D models show differences in both the overall and fine morphology (table 3.5, figs. 3.7 and 3.8).

“For numismatists the shape of the coin edge is regarded to be an important feature to characterize a coin” (Huber-Mörk et al. 2012, 135). The shape has therefore been characterized through maximum diameter and thickness, surface area, perimeter, and shape factor (also referred to as “circularity”).

3D data processing software	Acquisition resolution**	3D data acquisition system model
CloudCompare	100 µm	IDENTIK 300L / AriusTechnology
n/a	10 µm	Micro-Epsilon
Meshlab	127 µm	NextEngine Desktop 3D Scanner
n/a	n/a	Phoenix Nanotom 180 (GE)
n/a	50 µm	n/a
Matlab	13 µm (XY)	IDENTIK 300L, Arius Scanner; Nikon D200, Nikkor 200mm Macro Lens, f/5.6
Photoscan (Agisoft)	n/a	Canon 600D; Canon Macro Lens EF 100 mm 1:2.8, f/18 (v0.8, ISO100)
FlexScan3D	n/a	MechScan 3D Macro Scanner; Makro-IRIS Schneider-Kreuznach Componon-S 4/80 Unifoc f/6
OPTOCAT 2015R2	20 µm (XY) 3 µm (Z)	smartSCAN HE with 8 MP colour stereo cameras, FOV 75
n/a	n/a	Custom

Table 3.4. Basic topological measurements of the complete 3D digital surface models (i.e., obverse and reverse aligned and merged into one single model) computed with four distinct software packages: CloudCompare, Geomagic, Meshlab, and Polyworks. © Vera Moitinho de Almeida, 2016.

	Coin A		Coin B	
3D model	**Vertices** (Points)	**Triangles** (Faces)	**Vertices** (Points)	**Triangles** (Faces)
(SLS) Smartscan	518,454	1,036,902	251,967	503,930
(SLS) Mechscan	1,342,685	2,685,266	1,262,963	2,525,663
(SfM) Canon	200,002	400,000	421,118	842,232

Table 3.5. Basic geometric measurements of the complete 3D digital surface models (i.e., obverse and reverse aligned and merged into one single model) computed with four distinct software packages: CloudCompare, Geomagic, Meshlab, and Polyworks. © Vera Moitinho de Almeida, 2016.

	Coin A						
3D model and software	**Max. diameter** (mm)	**Max. thickness** (mm)	**Surface area** (mm^2)	**Volume** (mm^3)	**Peri-meter** (mm)	**Shape factor**	**Density** (g/cm^3)
(real world coin)	–	–	–	323.5		–	9.57
(SLS) Smartscan						0.96	
CloudCompare	17.95	2.59	539.11	336.42	–	–	9.2
Geomagic	18.03	2.58	539.11	336.42	–	–	9.2
Meshlab	17.95	2.59	539.11	336.42	–	–	9.2
Polyworks	17.95	2.59	539.11	336.42	56.25	–	9.2
(SLS) Mechscan						0.92	
CloudCompare	17.99	2.56	549.13	325.39	–	–	9.51
Geomagic	18.00	2.57	549.13	*inv. value*	–	–	–
Meshlab	17.99	2.56	549.18	325.39	–	–	9.51
Polyworks	17.99	2.56	549.13	325.39	57.24	–	9.51
(SfM) Canon						0.96	
CloudCompare	18.28	2.54	525.42	318.6	–	–	9.71
Geomagic	17.80	2.55	525.42	318.6	–	–	9.71
Meshlab	18.28	2.54	525.43	318.6	–	–	9.71
Polyworks	18.28	2.54	525.42	318.6	55.58	–	9.71

"In some coinages the comparison of weights among series may determine the standard to which that series was struck; this in turn may be significant for chronology or attribution" (ANS 2016, n.p). To estimate the composition—relevant "to identify differences between the theoretical and the real density when coins were plated (for instance, a silver over a copper core)" (Zambanini et al. 2009, 51)—the density of each coin was determined through weighing (at RBINS and ITAM) and calculating the surface volume of each 3D model, as well as through using a gas pycnometer (Micromeritics AccuPyc II 1340; at ITAM). The latter exposes the coins to vacuum and helium gas, and takes into consideration accessible voids, that is, the total amount of void space accessible from the surface of a real coin (Valach 2016). However, one should be cautious when interpreting density as

Coin B						
Max. diameter (mm)	**Max. thickness** (mm)	**Surface area** (mm²)	**Volume** (mm³)	**Peri-meter** (mm)	**Shape factor**	**Density** (g/cm³)
–	–	–	338.3		–	8.42
					0.99	
17.72	2.56	530.64	350.44	–	–	8.13
17.75	2.56	530.64	350.44	–	–	8.13
17.72	2.56	530.65	350.44	–	–	8.13
17.72	2.56	530.64	350.44	54.18	–	8.13
					0.97	
17.77	2.51	539.28	342.35	–	–	8.32
17.74	2.54	539.28	*inv. value*	–	–	–
17.77	2.51	539.3	342.15	–	–	8.33
17.77	2.51	539.28	342.17	54.59	–	8.32/3
					0.98	
16.48	2.56	514.93	337.51	–	–	8.44
17.54	2.49	514.93	337.5	–	–	8.44
16.48	2.56	514.94	337.5	–	–	8.44
16.48	2.56	514.93	337.5	53.88	–	8.44

these coins have a different chemical and elemental composition (including more than one element) and they may contain accessible and/or inaccessible voids.

The 3D models enabled a quantitative characterization of the coins, as opposed to a descriptive and subjective assessment. As expected, distinct systems, methods, and techniques used to acquire, process, and analyse 3D data led to differences in the topology, as well as in the overall and fine morphology of the coins. A larger data set or reference collection would be needed for the comparison and interpretation of further relevant geometric and other features. Depending on the reasons or questions behind the research, as well as the type and scale of analysis, the accuracy, resolution, and precision of the 3D systems and techniques should be enough to fulfil the needs for an improved scientific documentation and study

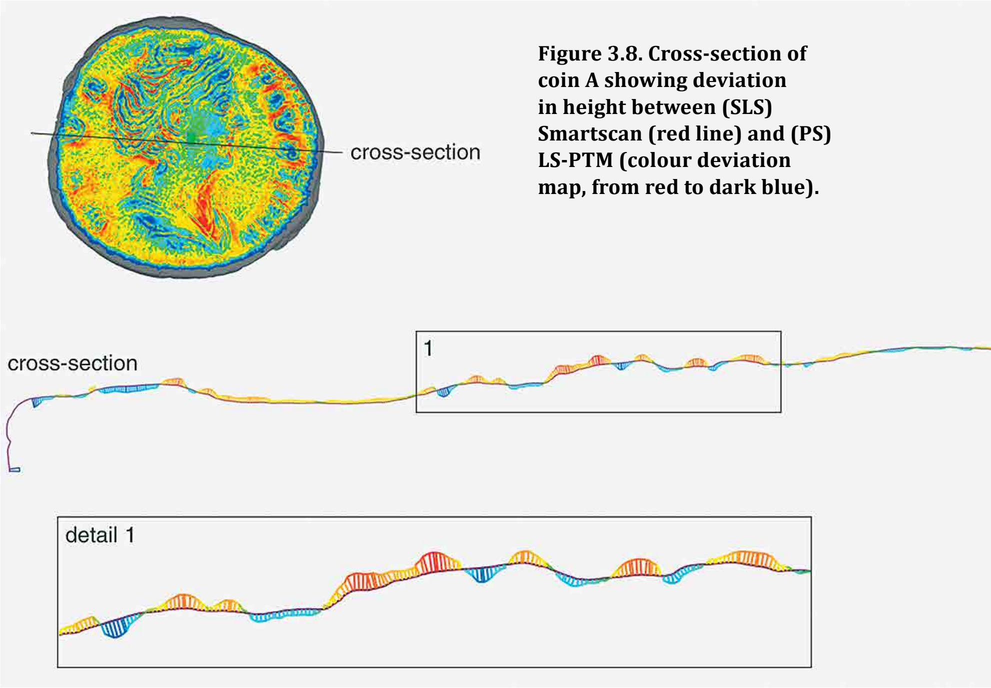

Figure 3.8. Cross-section of coin A showing deviation in height between (SLS) Smartscan (red line) and (PS) LS-PTM (colour deviation map, from red to dark blue).

of coins. These issues are of great importance, as they may affect the analysis, classification, and interpretation of the cultural heritage object—e.g., variations in the hammering process, die, mint signs, scratches, wear pattern of the used stamp, or cut and punch-marks. This also raises the importance of linking metadata, paradata, and other meaningful information to the data.

Although a 3D digital model does not provide a complete representation of the object, it should be understood as a highly powerful tool—potentially, with valid data—for cultural heritage research, and complementary to other measurement techniques (as used in this case study) and fields of knowledge (Moitinho de Almeida 2013).

XRF and SEM/EDX

To study the surface chemistry of the denarii XRF was used in conjunction with SEM/EDX. XRF analyses were conducted using three spectrometers, namely ARTAX 200, ARTAX 800, and S1 Titan LE, all produced by Bruker, Germany. No pretreatment was required; the coins were analysed as received. Both the two Faustina coins and the other two denarii in the study exhibited a high silver (Ag) content (>94%), as shown in table 3.6. The main constituents were Ag and copper (Cu).

Inset 1 shows an enlarged detail of the profile of the hair, whereas inset 2 shows an enlarged detail of the profile of one of the letters. © Lindsay MacDonald et al., 2017.

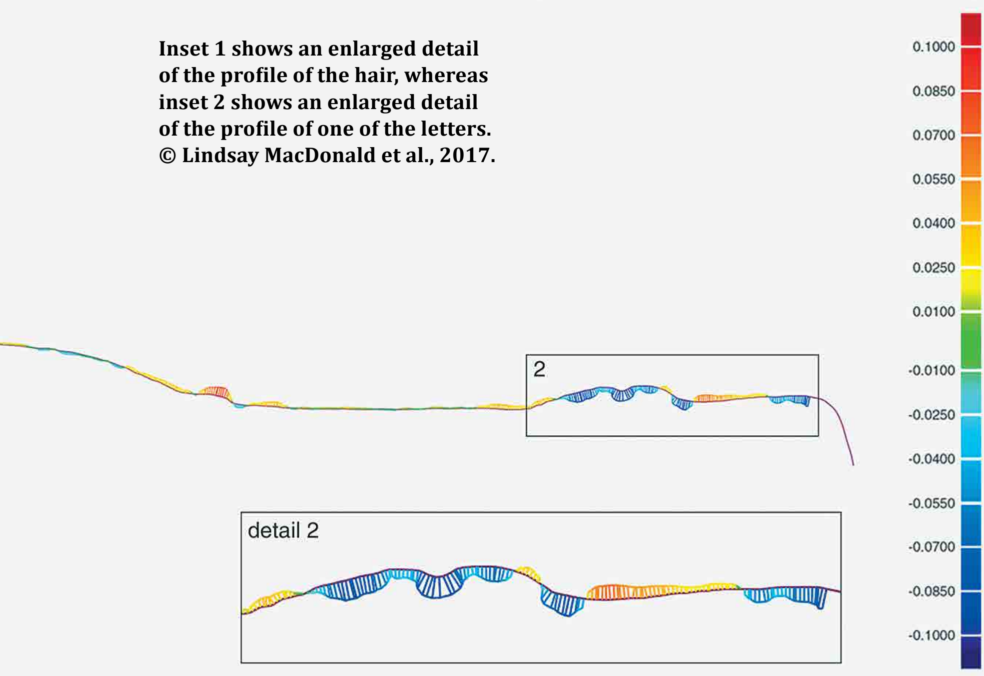

Table 3.6. A map of atomic composition of coins based on EDX analysis in SEM. The composition of the denarii of Faustina the Elder (A) and (B) is compared to two further denarii of Republican Rome (C) and Emperor Vespasian (D). The results at two measurement points are shown for each coin. The two grey columns indicate invalid measurements, where the instrument probe was over a point of the surface contaminated by oxidized carbon deposits. © Jaroslav Valach, 2015.

Element	A		B		C		D	
Ag	94.58	96.67	94.64	95.62	97.05	49.35	95.02	34.75
Cu	2.73	–	3.47	1.39	2.37	1.36	–	
Si	0.27	0.36	–	–	–	0.60	0.20	0.29
Al	0.12	–	–	–	0.16	2.51	0.20	0.17
Cl	–	–	–	–	0.02	2.99	–	3.42
S	0.20	–	–	–	–	0.60	0.45	0.84
C	1.40	1.71	1.21	1.34	–	26.27	2.82	46.39
O	0.70	1.27	0.69	1.65	–	10.70	1.32	9.38

Table 3.7. Quantitative XRF analysis of the evaluated coins by two instruments. For the Artax 200, concentrations are reported as the average of 6 and 12 measurements for coins B and A respectively. © Julio M. del Hoyo-Meléndez and CyI, 2015.

Instrument	Coin	Ag	Cu	Pb	Au
ARTAX 200	A	96.02 ± 0.75	2.95 ± 0.67	0.90 ± 0.14	0.14 ± 0.01
	B	97.90 ± 0.23	1.45 ± 0.18	0.44 ± 0.07	0.20 ± 0.01
S1-Titan LE*	A	93.0	4.3	1.5	1.0
	B	95.1	2.8	0.6	1.1

* The relative error for the S1-Titan LE is 2% for Ag and 30% for the remaining elements reported.

Other minor and trace level elements included lead (Pb), gold (Au), magnesium (Mg), silicon (Si), chlorine (Cl), calcium (Ca), manganese (Mn), iron (Fe), cobalt (Co), nickel (Ni), bismuth (Bi), and bromine (Br). Coin B also showed traces of antimony (Sb) (figs. 3.9 and 3.10).

Quantitative XRF and SEM/EDX analysis of the evaluated coins and comparison of two instruments are summarized in table 3.7. Although the penetration of SEM/EDX is lower than that of XRF, it can be seen that the results are generally in agreement. However, it is worth noting that the Ag concentration for coin B is lower in the SEM/EDX analysis. Due to the nature of the coins, the accuracy of the results can be influenced by a number of factors including: the existence of corrosion products, the presence of an Ag surface enriched layer, or the depletion of some elements. Therefore, it must be stressed that since micro-XRF results are not necessarily representative of the chemical composition of the bulk material, studying groups of coins with the aim of identifying similarities or differences in elemental composition is a better approach than trying to determine accurate values for each of the elements detected on a single coin.

In general, quantitative analysis carried out using micro-XRF, portable XRF, and SEM/EDX techniques has shown a reasonable agreement in the surface chemistry of the coins. These results indicate that XRF spectrometry can be effective for multi-elemental analysis of the surface composition of historic coins. Moreover the data can complement results obtained by other physical measurements and documentation techniques. The discussion of the effect of the instrument on the results is available at https://coschromancoins.wordpress.com/category/xrf/.

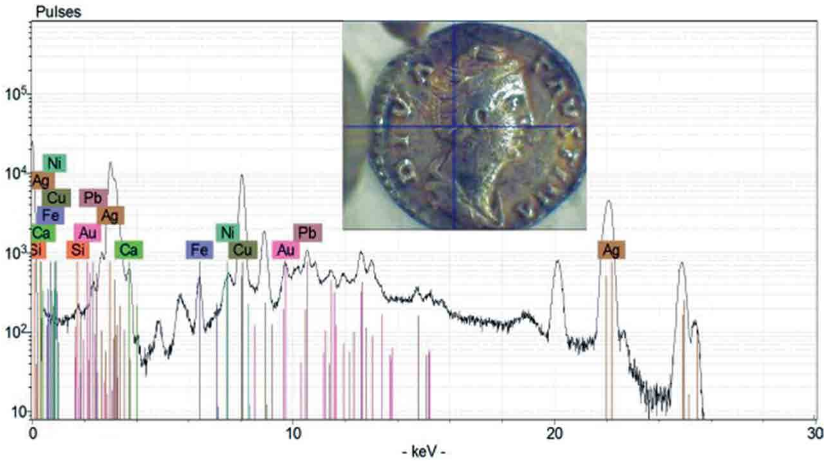

Figure 3.9. Micro-XRF spectrum of the point shown in the inset for the obverse of coin B. Unidentified peaks are likely due to three factors, namely interactions in the detector, X-rays contributed by the analysis system, and X-ray interactions in the sample. © Julio M. del Hoyo-Meléndez, 2015.

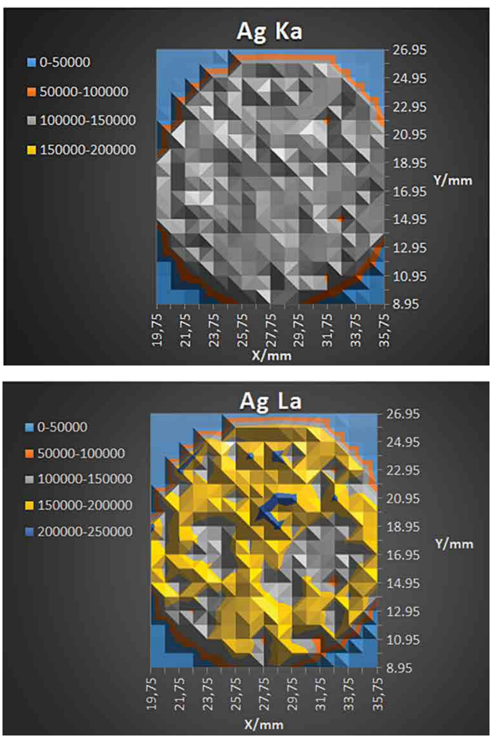

Figure 3.10. Elemental maps obtained by the Artax 800 instrument for the obverse of coin A showing Ag Ka (top) and Ag La lines (bottom). Although the map obtained for the Ka line shows that the coin is rather homogeneous, the less penetrating La line shows an uneven surface most likely associated with surface corrosion effects. © Julio M. del Hoyo-Meléndez, 2015.

MicroCT

There are significant differences in condition between the battered edges and overall wear of both coins, affecting how much of the original shape and decoration is still visible. An aureus (gold) or sestertius (bronze) of comparative design is likely to show more detail because, being harder, the metal can be engraved with more attention, and lesser production of dies was required. Although the wear on the two Faustina coins is to some extent visible to the naked eye, the microCT device (GE Phoenix microtomograph nanotom 180) revealed its full extent: areas of corrosion, cracks and other damage that cannot be seen under a magnifying glass (fig 3.11). The test also confirmed that the coins are solid silver (i.e., not plated) and revealed their composition (table 3.6).

Figure 3.11. Crack inside coin B visualized by microCT method (three perpendicular microCT sections and rendered 3D model). © Miroslav Hain, 2014.

Conclusions and Future Research

Two small historic coins, with a combined weight of less than 6 g, prompted an international, cross-disciplinary, two-year collaboration. Was it worth the effort of twelve COSCH researchers distributed throughout Europe, assisted by many colleagues, experts, and practitioners? Has the study achieved its objectives? What are the main contributions to the fields involved? Better recording? Accurate measuring? Comparison of data from different instruments? Meaningful characterization of the coins? What lessons in interdisciplinary research practice and communications have been learned? Each of these questions deserves independent discussion as this study impacted significantly on each of these topics. Importantly, a great deal has been learned about the two denarii. No evidence was found that would question their ancient provenance, indicated, *inter alia*, by the high content of silver. The fineness of the two coins seems to confirm their provenance from the Rome mint, AD 141. Further interpretation of the results indicating the content of silver (dependent on the slight variations between the instruments and methods used) is required; it is within known, authorized manipulation (to save on bullion), that is, the debasement of silver coinage under Antoninus Pius (Pense 1992). The later, extreme debasement of Roman silver coins (dropping to below 5 per cent silver content in the later stages of the third century) resulted, particularly in the provinces, in silver-plated copper denarii, contaminated with impurities. This and other aspects of the study point out the *critical* importance of reliable comparative evidence, or ground truth data, alongside expert opinion based on years of professional practice.

The coins travelled between multiple modern laboratories in the territories of the former Roman Empire where they once were a currency, and beyond. Bearing witness to the political, economic, social, cultural and personal histories of the period ca. AD 141–160, the denarii connected modern research, science, and technology with the past, and provided a stirring experience for those involved in the study. The coins were made available to all discussants of the methods applied to their examination and imaging, in the course of COSCH meetings and by independent experts.

Understandably, for conservation reasons, the privilege of the direct close observation and handling of historic objects is often denied to the public; access to *all* original objects required for a particular research project is rare. Advanced optical and spectrometric technologies in this study provide a means of virtual presentation of museum objects that to some extent compensate for these limitations. It should be stressed that visualization is not the primary purpose of metrological methods, such as 3D scanning or photogrammetry, while RTI, being an essentially photographic method, cannot measure the object's geometry. The resulting metrological and visual records may serve different uses, depending on the data capture technology. Information about the structural condition of the denarii gained through microCT is more reliable than the many, highly subjective descriptors used by numismatists, such as "worn" (W), "very worn" (VW), and "extremely worn" (EW) (Brickstock 2004, 7). Coin dealers rely on equally subjective grading scales, ranging from "poor" (P) to "very fine" (VF) and "extremely fine" (EF). Assessing the condition of historic coins could potentially rely on the presented quantifiable scientific methods. The wear on a coin exhibits the

Figure 3.12. Multimedia displays provide a vehicle for dissemination, *in situ* and online, of rich information about the object, its scholarship, and heritage science. Numismatic galleries of the Museum of Fine Arts, Boston, MA (left) and the Hutten-Czapski Collection, National Museum in Kraków, Poland (right). Screenshot of www.mfa.org, accessed 13 October 2015. Photo: A. Bentkowska-Kafel, 2016.

potential length of circulation; reliable methods of its assessment would benefit research into archaeologically derived coins. An interest was expressed in refining the microCT work to identify variations in density across a coin; this could be useful in understanding the production of blanks.

Some high-quality visual digital records created in the course of this study employ the highest technical standards currently available, allowing all-round, detailed viewing and provide information that is not available through traditional photographic 2D formats, whose use is still *a prevailing habit* in today's heritage documentation practice. RTI and 3D records meet scholarly requirements and are greatly appreciated by the interested public. Online viewing of such records is not without its problems, due to large proprietary files and specialist software, but is increasingly possible. Museums which have implemented modern collection management systems (CMS), particularly those which permit the connection of the main object record to its conservation records, have been encouraged to include comprehensive scientific data, if and where available, and to make them visible through public interfaces if appropriate (Bentkowska-Kafel et al. forthcoming). Once implemented by a local collection, a comprehensive numismatic record, with high quality, metrology-based visuals and relevant meta- and paradata, may be linked or integrated into a global resource—a practice started in November 2016 by OCRE, whose database now includes records from international museums.

The Hutten-Czapski numismatic collection of the National Museum in Kraków has a suitable information system and hardware infrastructure in place, and the required know-how to pilot public dissemination of heritage science through graphic interactive interfaces, on site and online. Display screens are available in the galleries to view details of coins in images that can be enlarged (fig. 3.12). The enhanced content of such displays, not only with RTI and/or 3D visualization, but also through explanation of scientific research and technology, is being advocated. Advances in haptic technologies hold the promise of virtual handling of heritage objects becoming closer to a life-like experience. Although machine haptics have been implemented for virtual surrogates of sculptures and other objects of cultural heritage, we are not aware of any systems for haptically enabled virtual numismatics.

The study and conservation of numismatics benefit from methods that can be applied to large numbers of objects. As a numismatist pointed out (communication 17 June 2014) "the 3D techniques would be of most use in projects such as die-linking, or trying to identify trends in wear from the same die, and possibly in the detection of modern forgeries." A digital method for identifying and comparing the punch-marks visible on the examined Roman Republican denarius would be of interest. "They occur throughout the empire it seems (and are probably some sort of testing or re-authorizing much later in their circulation) but their origin has not been pinpointed and they are poorly understood. [To be] tracked on different coins . . . die-linking would have to be employed to identify multiple copies of coins from the same die. In order to make this viable though it would have to be something that could be done cheaply and quickly so a great many coins/marks could be compared."

Our sample of two Faustina coins was too small to address such numismatic questions concerning the dies, their types, attribution, and versions (e.g., whether they were reworked), and further details of the technique of production, place, and period. As the coins were measured over two years, some changes over time, such as wear or possible damage and the effects of cleaning and tarnishing, were recorded but would be difficult to determine accurately because of the use of different instruments. A larger data set or reference collection would be needed for such a comparison and interpretation of relevant geometric and other features. Methods of scaling up the proposed applications of technologies, while reducing the cost per item, may be investigated with consideration of the inevitable trade-off between automation and respect for the uniqueness of every museum object.

It has been repeatedly pointed out that "museums have little money/time"; this being "one reason why [it is difficult to] foresee photography being replaced—we would aim for at least one hundred images a day but probably a lot more" (communication 17 June 2014). Conservation of coins at the British Museum involves cleaning large quantities of coins, potentially some 15,000 per year, particularly those found in hoards. The documentation of a coin, often still in the form of an index card, typically consists of two photographic records, information about material (e.g., silver), basic measurements (approximate diameter and apex), textual description, information about the provenance (often only recent), and iconography.

Due to the sheer number of historic coins in some collections and the relatively low value of most popular coins, many have not yet been properly recorded and photographed. When coins come from archaeological finds, where the context facilitates dating and authentication, additional tests may be redundant. The expert numismatists consulted were uncertain about a blanket need for and possible benefits of our methods, generally seeing them as superfluous to their routine research and conservation practice. The experts agreed that "Extreme examination of surface detail sometimes throws up production details such as legend engraver's guidelines or a recut", but they were dubious whether "the effort of 3D would pay off over good photography" (communication 14 June 2014). A need was articulated for reliable methods of identifying and imaging coins fused into a solid mass, for example in a cremation urn, without unduly disturbing it, or to avoid the expensive conservation work of defusing solid masses. One numismatist, incorrectly, expected RTI to help with this problem. The COSCH study was unable to investigate such finds *in situ* and could not address this particular question. RTI, as has been demonstrated, is effective for detailed surface imaging of flattish objects with relief, but it cannot represent 3D objects "in the round". It is a 2D technique which simulates three-dimensionality; it is not suitable for spatial recording and cannot penetrate a material structure.

Interest was also expressed in a non-invasive 3D technology that could "peel away" a suspected plated forgery to reveal its outer and inner layers, leaving them intact. If the denarii used in the COSCH study were counterfeit, the XRF and microCT examinations would plausibly have revealed a different chemical composition. Reliable comparative data are necessary in many such investigations.

Benefiting from access to a range of 3D imaging technologies—photogrammetry, laser scanning, structured-light scanning, photometric stereo—the coins were recorded in different laboratories using different instruments and setups. The study as a whole was a methodological experiment: advance planning was difficult due to lack of comparable previous experience and the unusual organization of the work. Researchers were joining in the course of the study, bringing new forms of expertise and making additional tests possible, thus expanding the scope in ways that could not have been fully anticipated. The voluntary nature of most of the work impacted on the originally agreed schedule and timely provision of the required data.

In a study of this kind a coherent method for recording the heterogeneous data and processes of individual measuring/scanning/imaging campaigns is needed to enable comparison of the multimodal results. Despite digitization of material objects being a long-established field, no readily available model and format for recording metadata and paradata was located. Metadata standards and recording guidelines are available for individual techniques and homogenous types of data.

Resorting to an Excel spreadsheet for recording the heterogeneous data collected in the course of multimodal measurements (available at https://coschromancoins.wordpress.com) was a practical yet problematic solution.

The study aimed to promote, after testing, a multi-method approach to the examination and recording of numismatics. We have studied current practice in selected museums and concluded that although the techniques and methods of the COSCH study are used in research, conservation, documentation, presentation, and dissemination of numismatics, they tend to be applied independently and not as a matter of *routine*. Academic projects of significance (e.g., Ponting and Butcher since the mid-1990s) generally depend on a series of research grants, lacking the continuity and opportunity to influence decisively different aspects of heritage or museum practice. These methods are generally too expensive and too time consuming to be applied systematically and across collections, to enable reliable and meaningful comparative studies. They require expensive instruments, and technical and scientific specialisms that are not readily accessible to museum professionals, even in the major national heritage institutions consulted. The indicative cost of a structured light system (as of 2015–16), that is, the equipment and its software, was €68,000; an alternative €30,000 system could have solved the same scanning task more cheaply, while compromising both the accuracy and resolution of the data. The time spent on the individual measurements varied between 2.5 hours per coin to several days required for 3D work (including preparation, measurement/scanning/imaging, data processing, meta-/paradata recording, and archiving) depending on the method and setup.

There is a difficult balance to be struck between the best possible and the best available applications of science and technology to the documentation and interpretation of museum collections. This study's approach was seen as prohibitively expensive and superfluous to actual requirements of the current museum research practice. The level of some museums' technological needs may be illustrated by a request for advice "What sort of computer do I need to set up a public display?" to show the disabled visitors what is upstairs (Schofield 2017). The request was addressed to a national British paper by a volunteer, who helps to run a small museum, and his budget was £250 ($300 USD). This example puts into context the need for the widest possible access to heritage collections as the ultimate reason for fostering technological solutions for museums.

Chapter 4

WALL PAINTINGS IN THE CHÂTEAU DE GERMOLLES: AN INTERDISCIPLINARY PROJECT FOR THE REDISCOVERY OF A UNIQUE FOURTEENTH-CENTURY DECORATION

CHRISTIAN DEGRIGNY and FRANCESCA PIQUÉ

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ABSTRACT

The aim of this study was to examine and document the wall paintings in the Château de Germolles. Situated in Burgundy, France, Germolles is the best preserved residence of the Dukes of Burgundy and was listed as a monument of national importance in 1989.

The medieval wall decoration of the Château de Germolles was rediscovered under the nineteenth-century plasters during World War II. Medieval accounts of the château provide a detailed list of the materials acquired to make the mural decoration, but this list is incongruous when compared with the current appearance of the paintings. The discrepancy between the archival and material evidence, and also the need to understand the complexity of the painting technique used were the main motivations for undertaking the case study described in this chapter. Imaging alongside more traditional examination techniques were utilized to record and document the mural decoration. The objectives of the case study were to distinguish the original materials from those applied during restoration, identify those materials, and correlate them with the archives. We also tried to understand the medieval painting techniques used and assess the condition of the paintings and stabilization requirements. Finally we aimed to find a sustainable solution for the management of the various types of data collected. Various techniques and investigations offered valuable insights into the materials and the painting technique used. To improve visitor experience, based on the information gained in the course of this study, a 3D virtual representation of the original decoration is currently proposed for display to the public visiting the Château de Germolles.

Keywords: Château de Germolles, dukes of Burgundy, Middle Ages, wall paintings, tin leaf decoration, spatial and spectral imaging techniques, COSCH

Introduction

The Château de Germolles dates from the fourteenth century and is the best preserved residence of the Dukes of Burgundy. The wall paintings decorating the ducal piano nobile are a unique manifestation of the courtly love that permeated the courts of French and Italian dukes and princes of the time. Concealed sometime in the nineteenth century, the wall paintings were accidentally rediscovered during World War II. They were non-professionally uncovered in the 1970s and restored in 1989–95. No technical documentation accompanied these interventions. Some important questions, such as the level of authenticity of the mural decoration and the characteristics of the original medieval painting technique(s) remained unanswered. In this project, some of the most innovative imaging and analytical techniques were combined to address some of these questions. The project provided not only significant information on the material and techniques used in medieval times, but also a thorough assessment of the condition of the paintings. The data collected are vast and varied. They required proper management, including the storage of large raw files with metadata and the alignment between data. Our investigations enabled us to hypothesize how the exposed medieval paintings might have been created and how they might have looked originally. Augmented Reality renderings were created and are now used to disseminate both the insights gained and the cultural significance of the paintings to the public visiting the château.

Earlier Research

Situated in Southern Burgundy, 10 km west of Chalon-sur-Saône, the Château de Germolles is one of the few late fourteenth-century ducal residences surviving in France. It was owned by Margaret of Flanders (1350–1405), wife of Philip the Bold (1342–1404), Duke of Burgundy (*reg.* 1363–1404) and brother of Charles V, King of France. Built between 1380 and 1400, Germolles evidences the rural interests of French dukes.

When the Burgundian branch of the House of Valois ended in 1477, the château became property of the successive French kings who passed Germolles onto close vassals. As illustrated in figure 4.1 the original enclosed château suffered damage at various points in time: the roof of the southwest corner was lost sometime in the eighteenth century and the corresponding walls were demolished after the French Revolution. In 1873 a section of the east wing was destroyed by fire, definitively separating the main building from the rest of the château. The present owners acquired the château after this disaster. The entrance gate was listed as national cultural heritage in the mid-twentieth century, while the rest of the build-

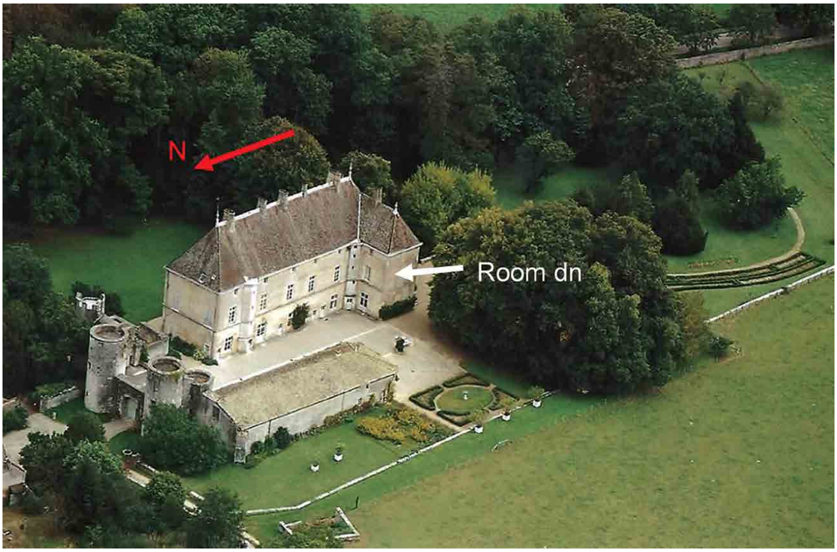


Figure 4.1. Aerial view of the Germolles estate from the northwest. The white arrow indicates the location of the room studied (dn) on the main building. The entrance gate is visible in the bottom left. The château was originally fully enclosed. Photo: Alain Rodrigue, 2007.

ing was listed in 1989 after the discovery of unique wall paintings dating back to the Dukes' period (Beck 2002). The château has been open to the public since the last fifty years and welcomes around 10,000 visitors per year.

Historic records held at the Archives départementales de Côte-d'Or (ADCO B4434-1) provide substantial information on the making of these paintings and their artists. The first (ducal) floor of the main building was decorated by one of the finest artist of the Burgundian School, Jean de Beaumetz and his workshop. Each of the adjacent apartments comprised a large bedroom and a corresponding dressing room. In modern times these apartments were divided, except the dressing room of Countess of Nevers, daughter-in-law of the Dukes. Her room, marked "dn" in figure 4.1 has survived in its original shape. In addition, all the rooms were redecorated with stucco plaster and wallpaper at the beginning of the nineteenth century. This new decoration was applied over the original wall paintings, which were keyed to improve adhesion of the stucco decoration. Some of this nineteenth-century decoration was removed in the 1970s after the rediscovery of the paintings in 1940. The paintings in the dressing rooms were restored between 1989 and 1995.

When entering the ducal floor, the visitor encounters on the walls a regular pattern of flowers—thistles, marguerites, roses—on a green background. In some

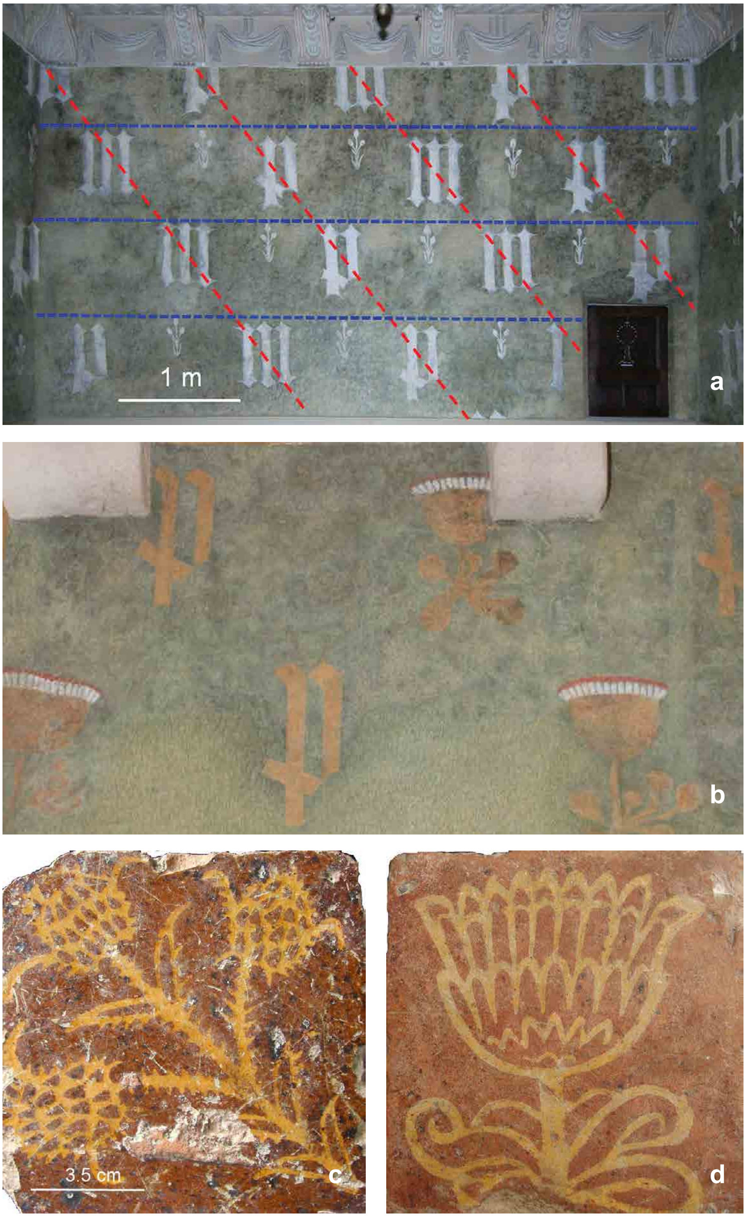


Figure 4.2. Details of wall paintings after conservation 1989–95
(a) in the dressing room of the Countess of Nevers; the red and blue dashed lines show the repetitiveness of geometrical pattern; (b) in the dressing room of Margaret of Flanders; (c) and (d) floor tiles reproduce the floral decoration of the walls. Photos (a) and (b) Francesca Piqué, 2013; (c) and (d) Château de Germolles, 2008.

rooms they alternate with large initials of the first names of the Duke and/or the Duchess (fig. 4.2).

The decoration of the dressing room of Countess of Nevers consists of series of letters P, letters M, and thistles, alternating horizontally (shown by blue dashed lines in fig. 4.2a) and aligned diagonally (red dashed lines in fig. 4.2a). Figure 4.2b shows similar horizontal and diagonal patterns with letters P and marguerites, or daisies, in the dressing room of Margaret of Flanders. The decoration of the rooms included floor tiles matching the flowers depicted on the walls (fig. 4.2c–d). All the flowers are symbolic. Thistles speak of fidelity or protection, while marguerites in blossom refer to the Duchess's name and young age. These motifs were characteristic of the courtly love that was fashionable in the late fourteenth century.

The medieval accounts (ADCO B4434-1) of the château record the materials acquired to make the mural decoration and a detailed list of these materials provides useful information for the study of the paintings. However, the composition of the extant paintings and the materials identified do not match this information accurately. In particular, the records account for a large quantity of metal leaves, which are not visible in the paintings. They were probably lost in the course of

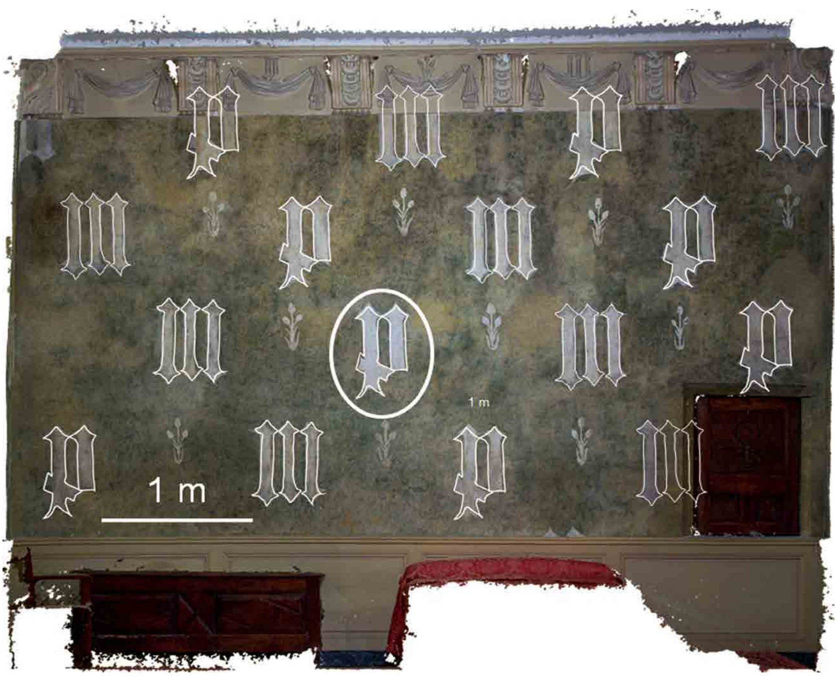


Figure 4.3. Orthophotograph of the west wall of room dn. The profiles of letters P and M are marked in white. The details of the letter P circled in white are shown in figures 4.4 and 4.5. Photos: Julien Guery, 2014; the outlines Château de Germolles, 2016.

centuries and through the uncovering operations. There is no mention in the accounts of a green pigment, which is extensively used in the background. This intriguing mismatch between the archival and material evidence, as well as the question of authenticity of the paintings, were the reasons for setting up our Germolles case study, conducted as an activity of the network, Colour and Space in Cultural Heritage (COSCH). Imaging and other non-invasive techniques, alongside more traditional examination techniques, were used to record and further document the mural decoration. All the exposed wall paintings were examined, but this chapter focuses on the comparative observations and analyses conducted in the dressing room of the Countess of Nevers, that is, room dn (Degrigny et al. 2016).

Description of Work

Preliminary Documentation

Basemaps of the walls were first created to document all future work. A photogrammetry campaign, using a Canon EOS 6D digital camera equipped with a 16 mm zoom lens, provided the orthophotographs. These digital images were used to manually trace the outlines of the letters. Figure 4.3 shows that on the west wall all M and P letters respectively seem to have the same form.

The extent of conservation work carried out in the twentieth century was revealed by infrared (IR) pictures (approx. 830–1000 nm) of the details of the walls, produced with a modified Canon EOS 5D Mark II digital camera which was equipped with filters and illuminated with a halogen Lowel V (500 W) light (Piqué 2013). Owing to the difference in IR absorption between the original and the repainted green background, the infrared pictures show clearly both the original and non-original areas. The losses caused by the nineteenth-century keying process were filled after the concealing stucco plaster had been removed. The missing decoration was recreated over these fills by repainting with material of

Figure 4.4. VIS and IR (approx. 830–1000 nm) photographic images of the letter P highlighted in figure 4.3. Arabesques in the lower part of the letter P are indicated in the VIS image. They seem to disappear in the IR image. Photos: Francesca Piqué, 2016.

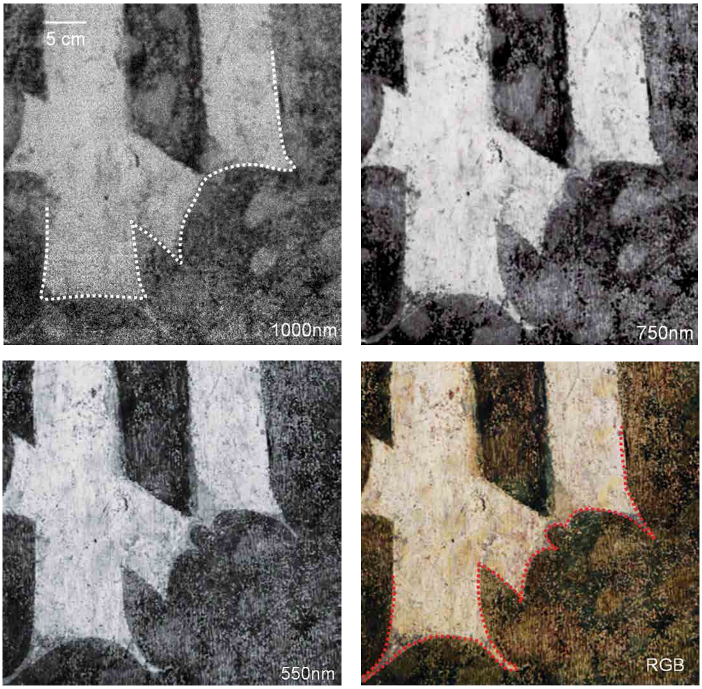


Figure 4.5. Hyperspectral imaging of the lower part of letter P, shown in figure 4.4. The white dotted line in the image at 1000 nm shows the original profile of the letter while the red dotted line in the RGB picture shows the profile of the embellished letter. Photos: Aurélie Mounier, 2016.

high IR reflection, while the authentic copper-based green which remained in the original portions of the plaster, had low IR reflection (high absorption) (fig. 4.4).

Furthermore, the embellishments (such as the arabesques) at the lower extremities of the P, in figure 4.4, are less visible in the IR image. Hyperspectral imaging was used to investigate these embellishments further. The CCD camera (HS-XX-V10E), developed by SPECIM, has a 1600 × 840 pixel resolution, a spectral resolution of 2.8 nm and a wavelength range between 400 to 1000 nm. The wall paintings were illuminated by two halogen lamps oriented at 45°. The data processed with ENVI 5.2 + IDL software produced an RGB image (R = 650 nm; G = 540 nm; B = 450 nm) and grayscale images at wavelengths ranging from 500 to 1000 nm. These pictures were used to indicate specific features such as the original profile of the P letters (a dotted white line in the image at 1000 nm, in fig. 4.5) and their embellishment by the medieval artists (dotted red line on RGB image, in fig. 4.5). The arabesques were added over the original green background and each letter P was embellished differently.

Stratigraphy of Paint Layers

The Letters

A close-up, visual examination, portable microscopy, and micro-technical photography (Dinolite digital microscope AD4113T) were combined to determine the stratigraphy of the mural decoration (fig. 4.6) (Papiashvili 2015). They revealed that the same technique was used to paint the letters P and M. The stratigraphy of paint layers is as follows: the white preparation layer (no. 2 in fig. 4.6) was applied on the support and was covered with a yellow underlayer (no. 3 in fig. 4.6). The letters were executed afterwards with a white paint (layer no. 4 in fig. 4.6) which looks heavily cracked.

The elemental analysis of these layers was carried out with non-invasive X-ray fluorescence spectroscopy (XRF) using a Thermo Scientific Niton XL3t 900 spectrometer equipped with a 50 kV X-ray tube with silver anode max. 40 μA and a Si detector with 195 eV resolution (Piqué 2014). The preparation layer (2) is rich in calcium (Ca) while the yellow layer (3) contains iron (Fe) and the white paint layer is rich in lead (Pb). Traces of titanium (Ti) and zinc (Zn) were detected. Micro-destructive examination by Laser Induced Breakdown Spectroscopy (LIBS) using a Nd:YAG laser in the fundamental wavelength (1064 nm) with 45 mJ energy

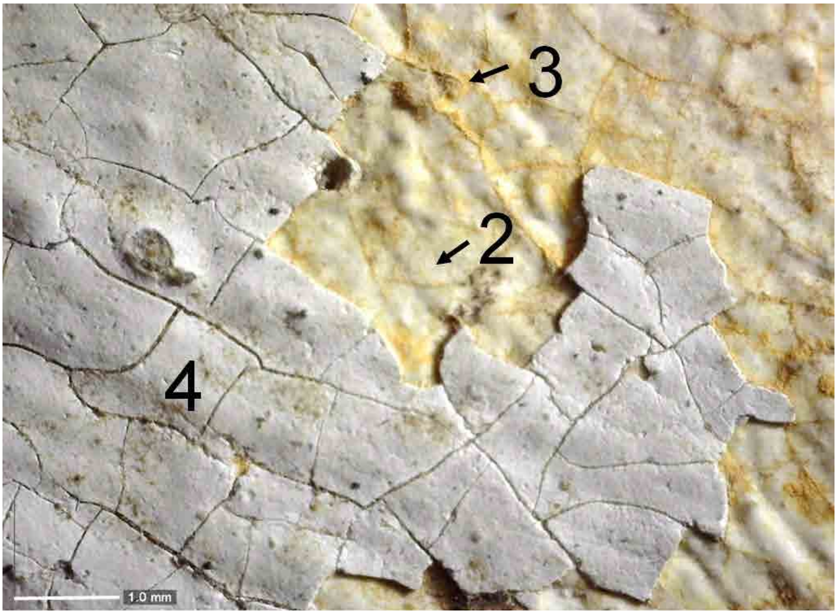


Figure 4.6. Micro observation of a letter M under a Dinolite® microscope. White ground (2), yellow (3), and white (4) paint layers. Photo: Nutsa Papiashvili, 2015.

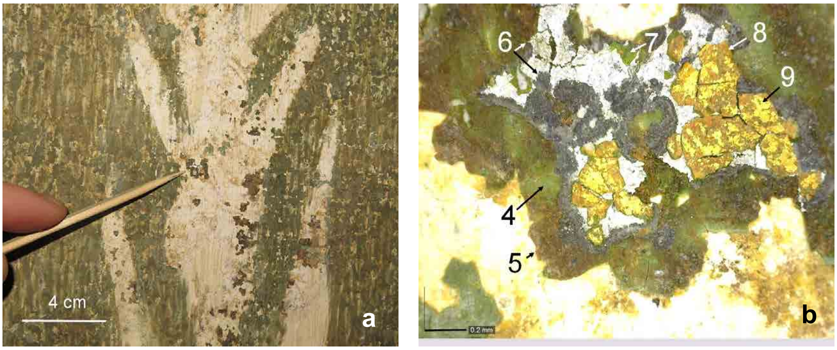


Figure 4.7. Macro (a) to micro (b) observation of a thistle under a Dinolite® microscope. The stratigraphy comprises the underlayers (preparation and yellow layers, the green background (4) and the finishing metallic layers (5 to 9). Photos: Nutsa Papiashvili, 2015.

focusing on 250 µm, 3 Ocean Optics range between 200 and 950 nm (from 200 to 340 nm and from 335 to 445 nm, 1800 mm^{-1} grating, resolution 0.1 nm; from 510 to 940 nm, 600 mm^{-1} grating, resolution 0.31 nm) spectrometers and data processing with CALIBSO software confirmed the presence of Zn and Ti on the white paint layer. Barium (Ba) was also identified, suggesting that possibly lithopone (barium sulphate combined with zinc sulphite) and titanium oxide were used during the recent conservation work. Other elements (Pb, Fe, and Ca) were also confirmed in the layers below.

The Thistles

At the time of writing (2016) most of the thistles appear white because only the white Ca-based preparatory layer remains (figs. 4.2a and 4.7a). Green paint layers, as well as the isolated black remains of decoration, are visible in small amounts (fig. 4.7a) where they have not been toned down by white repainting applied during the 1989–95 conservation campaign (Piqué 2013 and Papiashvili 2015).

Visual observation and examination under a portable microscope both revealed a green layer above the yellow underlayer (no. 4 in fig. 4.7b). The green layer corresponds to the overall background of the entire wall. This shows that the thistles were painted over this green background layer. The sophisticated thistle decoration is almost completely lost, but microscopy examination of the remains shows that it was extremely complex and comprised a number of metallic foils (fig. 4.7b). The following order of layers was identified, from bottom up: an orange layer (5) a silvery layer (6) covered with a transparent green layer (7) covered with another orange layer (8) with a gilded layer (9) on top. The systematic analy-

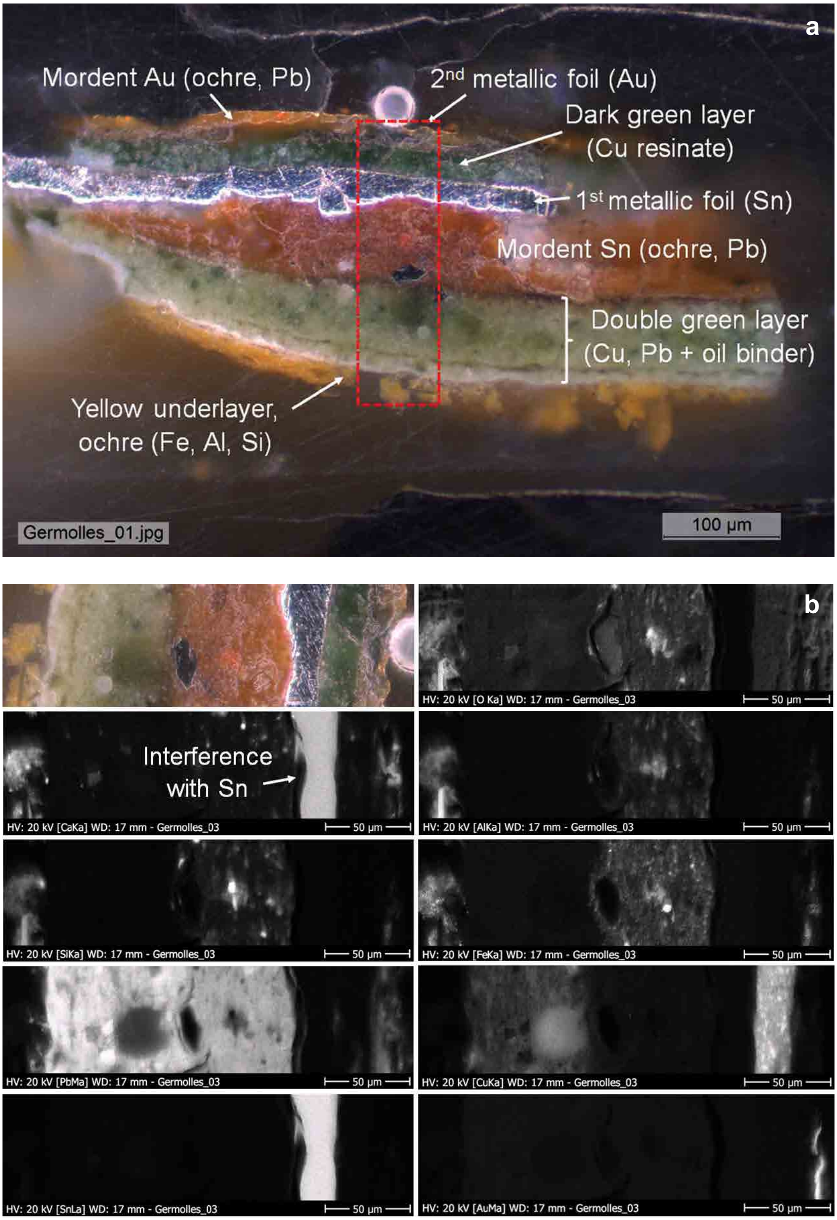


Figure 4.8. Cross-section of a fragment from a thistle, observed in visible light under an optical microscope. The identification of the material was carried out by combining (a) FTIR and SEM-EDS analyses; (b) elemental mapping of the area in the red, dashed rectangular. Photos: Francesca Piqué, Dominique Martos-Levif, and Stephan Ramseyer, 2015.

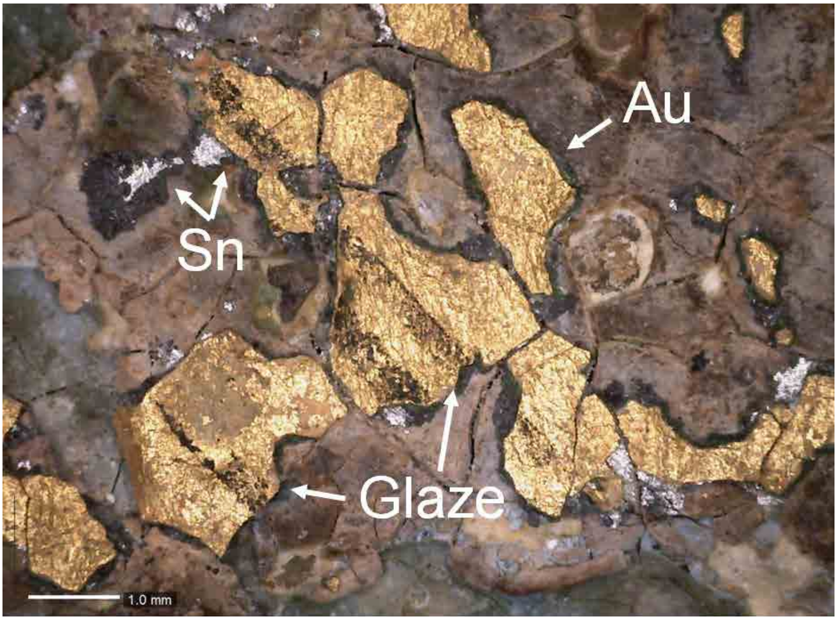


Figure 4.9. Micro-photography of a gold leaf from a thistle in the upper parts of room dn, showing traces of a black glaze or paint layer. Photo: Francesca Piqué, 2014.

sis of these metallic remains by XRF revealed that the silvery layer is tin (Sn)-based (Piqué 2014). Tin oxidizes with time and turns black as shown in figure 4.7b. The top layer was made of gold (Au), while copper (Cu) and Pb were identified on the green background layers. LIBS has confirmed these results.

A small detached metallic fragment of the thistle stratigraphic decoration was mounted in cross-section and examined under an optical microscope. The complete stratigraphy identified visually was confirmed as all layers could be visualized from the powdery yellow underlayer to the upper gold leaf (fig. 4.8a).

Each cross-section layer was further characterized with energy dispersive spectroscopy associated to scanning electron microscopy (EDS-SEM) using JEOL JSM-6400 at a voltage of 20 kV, as well as Attenuated Total Reflectance - Fourier Transformed Infrared (ATR-FTIR) spectroscopy using PerkinElmer spectrum 100 equipped with deuterated-triglycine sulphate (DTGS) detectors (4000 to 400 cm^{-1}). The yellow underlayer contains both Fe, aluminium (Al), silicon (Si), and Ca and is probably yellow ochre rich in clays. The green background consists of two layers both containing Cu and Pb, but in different ratio. The first layer is whiter and contains mainly lead white $(PbCO_3)_2Pb(OH)_2$ while the second is greener and is richer in a Cu-based green. The binder of these Cu and Pb based layers is probably

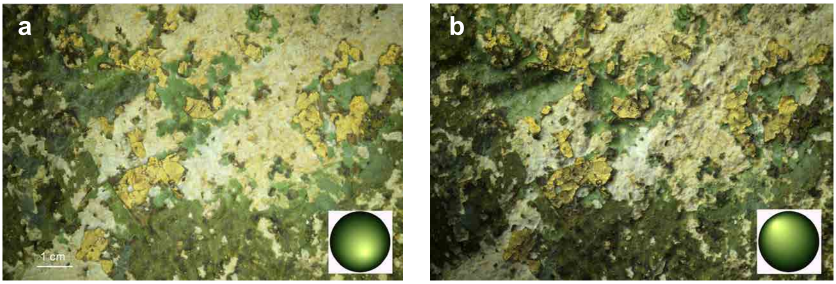


Figure 4.10. H-RTI snapshots under different illumination angles. Gold remains are evident in image (a) but not so much the stratigraphy of layers. The reverse is observed in (b), when the surface is illuminated from the opposite direction. Photos: Gaëtan Le Goïc, Alamin Mansouri, and Château de Germolles, 2015.

oil, as identified through FTIR spectroscopy, and certainly walnut oil, as listed in medieval records (Nash 2010). The orange layers under the metallic leaves have a variable thickness and act as mordants for these layers. Both contain an ochre with Pb and walnut oil. The green layer on top of the tin is a copper resinate, as identified through FTIR spectroscopy (fig. 4.8b). A black glaze or paint layer was observed on top of some of the gold foils. It was certainly applied to give some relief to the gold background (fig. 4.9) (Mounier 2010).

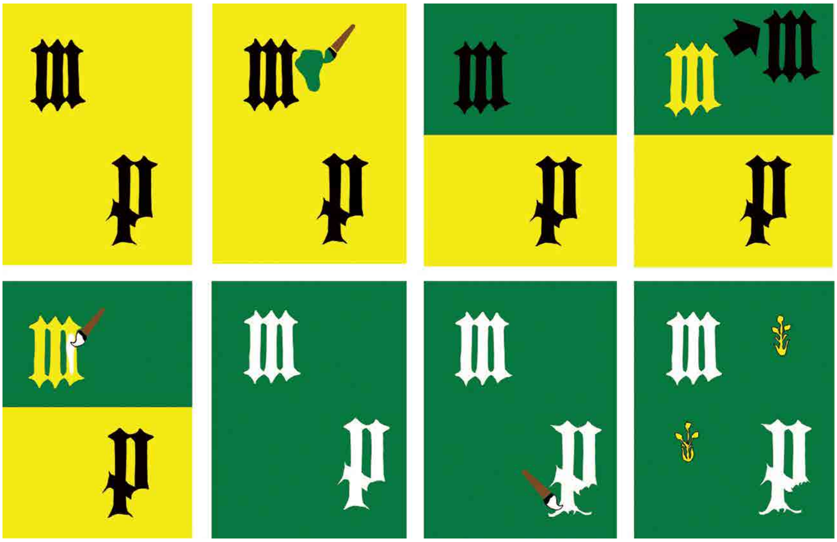


Figure 4.11. Representation of the steps in the historic process of decorating the dressing room of the Countess of Nevers with murals. Photo: Château de Germolles, 2016.

Highlight-Reflectance Transformation Imaging (H-RTI) using a Nikon D 7100 digital camera equipped with a zoom lens (DX-VR, AF-S 18–140) used with maximum magnification (140 mm), at a working distance of approximately 25 cm, was tested as an alternative to raking light to better visualize the details and stratigraphies of these paintings (Duffy 2013). The surface under observation was illuminated with a torch equipped with an LED of a power of white light (XM L2). Figure 4.10 shows two snapshots of a detail of a thistle, rendered using the Polynomial Texture Mapping (PTM) reconstruction method from an H-RTI recording. The remains of the gold foils are clearly visible in figure 4.10a, while the stratigraphy of layers is more visible in figure 4.10b.

Painting Techniques Used

The data collected allow us to hypothesize about the original painting techniques used at Germolles by medieval artists (fig. 4.11).

The lime-based preparation layer was first covered uniformly with a yellow ochre underlayer. The large letters P and M were created using stencils, while the green background was painted all around the stencils, in two sub-layers with different Cu/Pb ratio, probably bound with walnut oil. The letters were painted afterwards on the yellow ochre using lead white in walnut oil. The profile of the M letters was not modified further. The arabesques were painted over the green background at the extremities, particularly the lower ones, of the P letters. Thistles were applied in between letters over the green background with mordant. They were made of green tin foils, cut in the shape of the flowers, gilded and further decorated with black glaze or paint layer. The medieval accounts record large quantities, almost 2000 pieces, of green tin foils. This was the largest purchase of this foil by any residence of the Dukes (Nash 2010). Figures 4.8, 4.9, and 4.10 show these metal foils used to make the metallic thistles over the green background. Lead white was used to produce the background as well as Cu-based green, certainly produced locally.

Conservation Condition

This study was an opportunity to characterize the colour of the paint layers and their possible modification over time. A Minolta CM-700d handheld spectrophotometer was used to compare the reflectance spectra of a recently exposed green background and portions uncovered in the 1970s (Piqué 2014). The results showed that this colour had not changed significantly. Apart from their embellishment, another interesting feature of the P letters is the greyish colour in some areas along their profile (fig. 4.12a). This could be a result of the well-known lead white alteration process (Giovannoni et al. 1990). It is noteworthy that this pos-

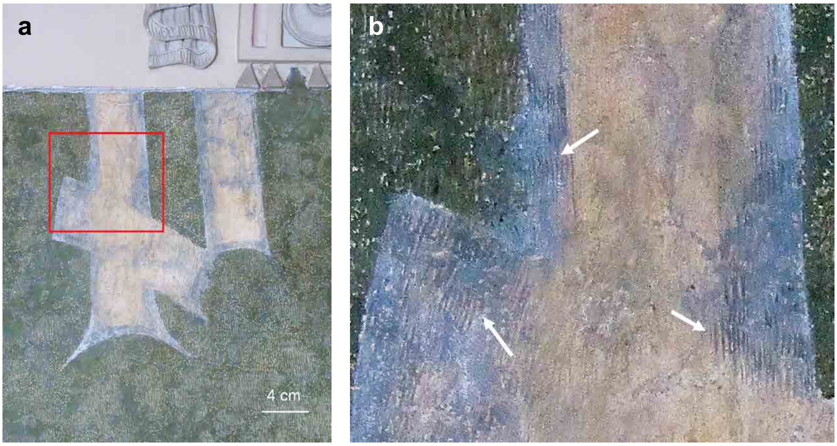


Figure 4.12. (a) Alteration of lead white, creating a shadow effect, observed on the edges of a P letter; (b) details of repainting (indicated by white arrows) the same P, applied in the course of the conservation campaign of 1989–95. Photos: Château de Germolles, 2015.

sible alteration seems to be limited to areas where the lead white is covering the Cu-based green background. The repainting carried out at the end of the conservation campaign emphasized these features further (fig. 4.12b).

Due to the ageing of the mural decoration and its alterations in the course of the application of modern plasters, followed by their removal in the 1970s, only traces of metallic decoration have survived. The cross-section of figure 4.8 shows that the layers from the green background to the top gold layer are well attached to each other. This might explain why only the yellow underlayer often remained on the white preparation layer, once the top metallic layers got detached.

A close observation has revealed a complete stratigraphy of layers (where preserved) in all parts of the thistles (flowers, leaves, and stems). This suggests that all the flowers were fully gilded. It is noteworthy that green and not white (not coloured) tin was used. What for, if not to be seen? Green tin was much more expensive than white (Nash 2010).

With the exception of the flaking of some metallic remains, the paint layers are generally stable and adhere well to the surface of the walls. This might be explained by the overall surface consolidation with a solution of Paraloid B72®, carried out during the 1989–95 conservation campaign (Takahashi 1991–94). Visual examination and active IR thermography (IRT) revealed major detachment problems in the upper parts of paintings, below the nineteenth-century cornice. The room was heated artificially to capture images using Thermocamera testo 890 equipped with IR-FPA (focal-plane array) detector. During the dynamic IRT

Figure 4.13. (a) Graphical representation through IRT of areas of detachment in the north wall of room dn; (b) representation (overlaid onto an IR image) of similar areas, in blue, as recorded by tactile assessment (knocking method). Photos: (a) Cristina Tedeschi and Marco Cucchi; (b) Nutsa Papiashvili, 2015.

the detached zones heat up faster and could be distinguished with respect to the sound zone. A digital threshold filter was used to retain only pixels which are above a certain temperature and to remove all the others. Figure 4.13a shows the results achieved in room dn, on the north wall. When compared to the graphical representation of the tactile assessment (knocking tests), both results were very similar (fig. 4.13b). The same results were achieved on the other walls, indicating that detachment problems occur on all four walls of the room (Tedeschi 2016).

Alignment of Data

The vast and varied information gathered in the course of this research have contributed to a much better understanding of the materials and techniques used to paint the walls of the medieval residence and of the significance of the surviving decoration. However, the managers of the Château de Germolles are very concerned about the amount of data collected so far and how to manage it to ensure efficient archiving and access. Very large files that can only be visualized using specialist software are a challenge. The files need to be properly named, indexed, archived, and stored for future use.

The alignment of data is a field of research that requires specific expertise in data management (Manuel et al. 2013). Some preliminary tests on data acquired in the course of this case study were carried out (Degrigny 2016). For instance, using a photogrammetry-based point cloud of the room dn south wall, tie points (also called salient or dominant points) were detected over different imaging modalities (different cameras showing different spatial and/or spectral resolutions) such as the P letter in figure 4.14 (Degrigny 2015).

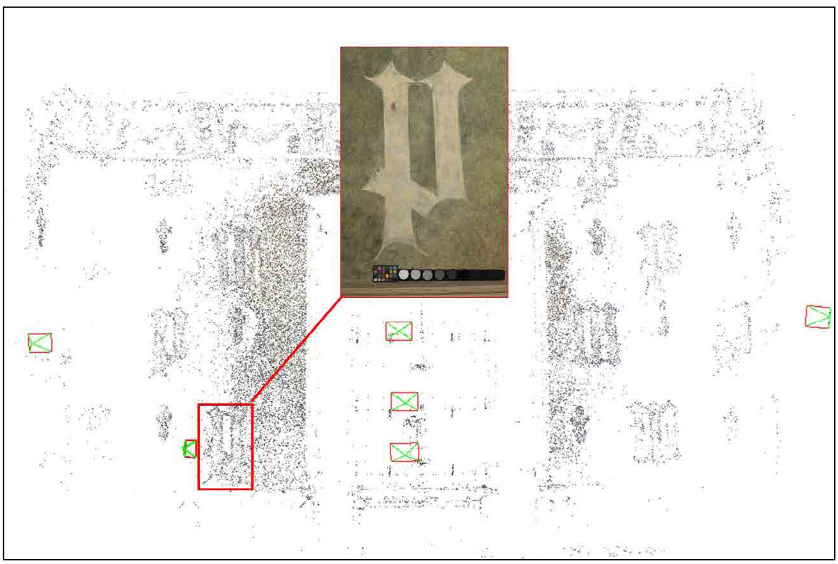


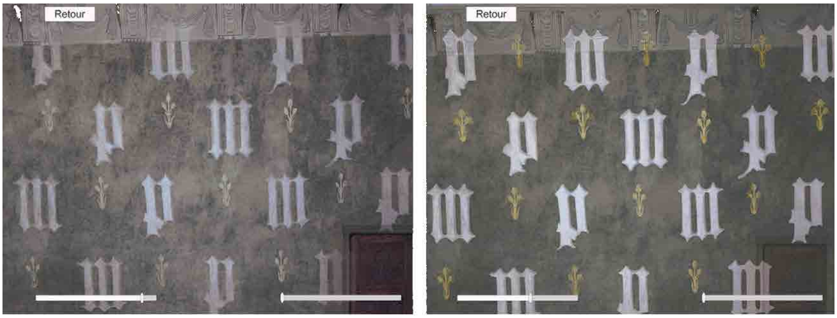
Figure 4.14. Tie points between the point cloud of the south wall of room dn and a technical picture of a P on the same wall. Photos: Anthony Pamart, 2015 and Francesca Piqué, 2013.

Figure 4.15. Snapshot from the SIVT application tested on Germolles case study data. The rectified and registered IR image of the P (red arrow) is displayed on top of the orthophotography of room dn south wall. Photos: Stefanie Wefers and Tobias Reich, 2016 and Francesca Piqué, 2013.

Another promising application, Spatial Image analysis and Viewing Tool (SIVT) (Wefers 2016) was tested to provide a combined visualization and analysis of images of the details of the Germolles wall paintings. Different 3D data sets, including orthophotograph of room dn south wall, were registered and integrated into SIVT as basemaps. Images of the details of the wall painting (such as an IR image of the same P as in fig. 4.14) were semi-automatically registered, allowing a combined visualization of the orthophotograph and detailed images (fig. 4.15). This alignment process may potentially enable locating pictures of the wall details, taken during a conservation campaign for documentation, condition monitoring, or conservation intervention.

Augmented Reality Tests

Dissemination of the information obtained was also a concern. The château being open to the public, the managers were interested in communicating to the visitors the outcomes of this study, in particular the new insights gained into the material history of the decoration. The use of Augmented Reality was considered as a very effective method and non-invasive approach. Tests were carried out on the west wall orthophotograph of figure 4.3. An application was developed for a tablet, using the Unity3D® game engine. A virtual scene was constructed from the



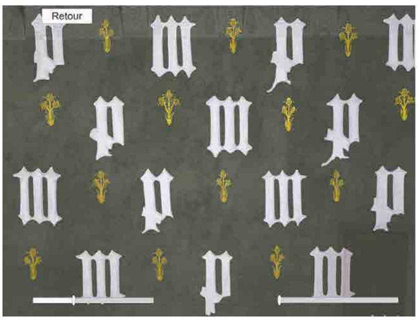


Figure 4.16. Composite visualization of the actual decoration (above) transitioning to the virtual representation (left).
Photos: Dorian Masson, 2016.

orthophotograph and existing data collected during the Germolles project: homogeneous green background, white M/P letters with arabesques for the latter, and thistles with different profiles but similar to the one found on the floor tiles (fig. 4.2c). When facing the wall with the tablet, natural markers (association of letters and thistles) from the orthophotograph of the wall are detected by the Kudan® Software Development Kit used and distances are calculated between the markers and the camera of the tablet. The direction vector of the marker is used to find the similar position on the virtual scene that appears on the tablet. To facilitate an appreciation by visitors of the virtual reconstruction, a joint visualization was created for the tablet that allows progressive movement from the real to the virtual scenes, as shown in figure 4.16.

Critical Discussion and Evaluation of Research: Future Work

The onsite examination of the Château de Germolles took place over a period of four years. This gave us the opportunity to test different techniques and eventually select those that were informative. Due to the limited funding and support received, however, the workflow was not the most appropriate. It also depended on the availability of the experts. Logically, the photogrammetric and IR thermographic surveys should have been carried out first, to create basemaps and assess the conservation condition of the paintings against their support. We could have continued with other non-invasive investigations, such as macro- and micro-VIS, UV, and IR technical photography, hyperspectral imaging, concurrently with XRF analysis, to assess the level of authenticity of the wall paintings. To better characterize the different stratigraphies of layers, H-RTI and LIBS could have followed on. The invasive examination of samples from cross-sections should have been conducted afterwards. These campaigns could have been accompanied by a final application of colorimetry to assess the colour modification of the paint layers. These results could be used for reference in future surveys.

Some results were more informative than others. The results achieved through the Structured Light Imaging (SLI) could not be exploited due to the lack of lens suitable for the capture of data at the required resolution. Similarly, we did not manage to achieve the level of visualization expected from H-RTI. This drawback can be easily overcome by using a more resolved camera (of higher spatial resolution) which would still make this technique very promising and more accessible to the end-users.

Small hatchings have been observed in the greyish areas along the outlines of the P letters. They are different from the retouching (regular hatchings) applied during the conservation campaign of the 1990s. Their analysis through LIBS revealed the presence of silver. This element could have been used in medieval times. Further investigation would be needed to determine the level of authenticity of other metallic traces. The surface rendering of the metallic thistles remains another important, open question.

The physical instability of the wall paintings has been revealed in close-up examination and quantitatively documented through IR thermography. A thorough survey of both the nineteenth-century cornice and the upper part of the wall paintings will be needed in the future.

Conclusion

By combining appropriate imaging and analytical techniques we managed to answer some of the questions raised initially, such as the authenticity of Germolles medieval wall paintings and in particular the use of tin foils and gold leafs mentioned in the medieval records. Furthermore the painting techniques used are now better understood: stencilling for the M and P letters with arabesques added to the latter and application with mordants of complex metallic decorations for the thistles. Finally the conservation condition of the mural decorations could be assessed: if the paint layers are rather adherent to the preparation layer, areas of detachment from the support have been observed on the upper parts of the walls that will require their thorough monitoring in the future.

The tools available within the COST Action COSCH, such as short-term scientific missions, and task force meetings have been essential in bringing to the Château de Germolles wall painting conservation professionals and imaging experts who have contributed to the study of the paintings and to the collection of documentation data. The interdisciplinary approach and the integration of the information obtained by the various experts were important to achieve this new level of knowledge. The financial support of DRAC-Burgundy made it possible for us to invite other French experts who joined the interdisciplinary team as constituted.

Among the imaging techniques tested at Germolles, some appeared particularly adapted to end-users. A COSCH training school as a final step in the case study demonstrated the possibilities of photogrammetry, technical photography, and H-RTI applied to the documentation of wall paintings.

The next challenge for the managers of the Château de Germolles is the alignment of all these data. We are just at the beginning of this process, but the new management tools under development are promising. In addition, data management, backup, and migration to new formats are fundamental tasks that will be performed in due course. The managers plan to pursue the Augmented Reality experience by expanding it to the four walls, the ceiling, and floor of Countess of Nevers' dressing room.

Chapter 5

A 4D VIRTUAL PRESENTATION OF THE WHITE BASTION FORTRESS IN SARAJEVO

SELMA RIZVIĆ

ABSTRACT

The fortress known as *Bijela tabija*, or the White Bastion is one of the most impressive and important historical sites in Sarajevo, Bosnia and Herzegovina. It is located on the southeast outskirts of the city and offers a view over the city valley. Historically it has commanded a significant and strategic position in the city. The fortification is a part of the dominant defensive walls that surrounded the old city of Vratnik.

The historical site presents various valuable strata, from the medieval era to the present. During archaeological excavations the remains were found of a medieval fortification from the fourteenth century, and from the Ottoman period in the seventeenth century when the fortification was expanded and some new structures were built. During Austro-Hungarian rule part of the fortification and the structures inside the walls were demolished and a new group of structures was built. During the early excavation, a significant number of artefacts was found, registered, and conserved for the purpose of the exhibition hosted in the Museum of Sarajevo.

Our project "4D Interactive Multimedia Presentation of the White Bastion Fortress", described in this chapter aims to present the historical development of this cultural heritage site through digital stories combined with interactive 3D models of the Bastion in various time periods. These models include digitized findings from the site and their 3D reconstructions.

Keywords: interactive digital storytelling, virtual cultural heritage, virtual reality, 3D virtual reconstruction, COSCH

Introduction

The age of interactive communication has changed the way people perceive information. All aspects of our lives are influenced by digital technologies. They introduced a new language, and new communication means and tools. Cultural heritage is no longer limited to museums and heritage sites, but is being communicated to the public through new methods and forms which enable users to travel virtually to the past.

Storytelling has been present in human communication since the beginning of time. Our ancestors used to tell stories and tales around camp fires. Every day of our lives can be described through a set of stories. Therefore, it is natural that storytelling plays an important role in cultural heritage presentation and its digital preservation. Museum exhibitions employ storytelling to explain the context and purpose of exhibited objects, in order to make the visitors' experience more attractive. Virtual reconstructions of archaeological remains are becoming enhanced with stories about the objects, characters, and events from their past.

Digital media applied to the study of cultural heritage engage interdisciplinary teams of researchers: historians, digital humanists, computer scientists, archaeologists, writers, psychologists, and visual artists. They work together seeking the most attractive, immersive, educational and entertaining methods in virtual presentation of cultural monuments.

This chapter recounts an experience of such a quest through the 4D interactive multimedia presentation of the White Bastion Fortress in Sarajevo. The term 4D alludes to the fourth dimension, time, in a three-dimensional presentation of the object. The White Bastion Fortress has been used to defend Sarajevo since the medieval period. It has changed over time as power has changed hands in the city. 4D virtual presentation aims to display the historical development of this site through digital storytelling combined with interactive 3D models of the Bastion in various historical periods. These models include findings from the site that have been digitized and some 3D reconstructions. A new method of interactive digital storytelling for cultural heritage was implemented.

Related projects that served as an inspiration for creating the application will be presented in what follows in this chapter. Our team's research in interactive digital storytelling will be described, and a new concept implemented in the White Bastion case study will be elaborated. The details of the implementation of the case study will be offered and the first user experiences, alongside some comments, presented. The chapter concludes by summarizing the results of research and indicating future work directions.

Earlier Research

Our research into related projects focused on cultural heritage presentations which included interactive 3D models of cultural monuments interconnected with digital stories about their past. We were interested in the user experience in exploring these applications, particularly in their feeling of immersion, quality of interaction, information perception, and entertainment value.

The Etruscanning 3D project (Pietroni et al. 2013) is a virtual presentation of the Regolini Galassi tomb, one of the most remarkable Etruscan graves, and the artefacts found within it. The application is a permanent installation at the Allard Pierson Museum in Amsterdam. Thanks to its digital nature, it has also travelled around many exhibition spaces. The digital content consists of a virtual model of the tomb. The models of artefacts found in it, and currently kept in the Vatican Museum, as well as stories told by two narrators, characters buried in the tomb are also included. The content is displayed on the projection screen and users can browse and activate stories through a natural interaction interface (instead of mouse and keyboard, the user communicates with the application using gestures which are captured by a motion sensor). This project offers an interesting combination of storytelling with a 3D environment of the tomb, along with interactive models of the artefacts found therein.

Livia's Villa Reloaded (Pietroni et al. 2015) is an innovative Virtual Reality installation dedicated to the Villa Ad Gallinas Albas. Livia Drusilla offered the villa as dowry to the Emperor Augustus when she married him in the first century BC. The installation introduces a novel approach to storytelling, combining different media and languages: real time exploration, cinematographic paradigms, use of real actors, and virtual set practices. Users may select different digital stories placed inside an interactive 3D reconstruction of the villa created from a laser scan of its archaeological remains. The communication within the application is through a natural interaction interface.

The European Virtual Museum Transnational Network of Excellence (V-MusT.net) has been researching and synthesizing the knowledge on digital cultural heritage for four years (2011–15). In their final exhibition, Keys to Rome (Pescarin et al. 2014) they showcased virtual reconstructions of Roman heritage in four geographic locations—Rome, Amsterdam, Alexandria, and Sarajevo—at the same time. The aim of this multimedia exhibition was to present life in various parts of the Roman Empire during the era of Emperor Augustus. It was created through a combination of physical exhibitions from four selected museums and digital content, connecting all four locations through online virtual heritage applications. One of the setups, called Admotum, was designed as a serious game where the visitor, through a natural interaction user interface, could walk around the virtual models of buildings from the Roman period in his or her location, while following the stories about objects from those buildings. The virtual models of museum artefacts were of archaeological finds. After successfully collecting all the objects in his or her location, the visitor could visit the other three locations of the exhibition, collect the objects there, travel "through" their monuments, and learn about them from digital stories. The educational potential of digital technologies applied to cultural heritage, together with the effectiveness of mixing up museum collections and technological applications, is presented in Pagano and Cerato (2015). The authors focus on the Keys to Rome exhibition held at the Imperial Fora Museum in Rome.

The virtual cultural heritage application setup in the Civic Museum of Schifanoia in Ferrara (Incerti and Iurilli 2015) presents the historical development of the Schifanoia Palace through virtual models of the palace in various periods. They are combined with narration about the main events that took place within and around it. The aim of the project was to enhance the experience of visitors through new communication strategies and tools, making the museum experience more complete and satisfactory.

The first three projects mentioned in this section facilitate communication between users and digital content through natural interaction interfaces. We consider these interfaces extremely suitable for museum installations, but not entirely appropriate for online implementation. The fourth project is also set up in a museum. In our project Internet access was needed for the virtual presentation, so the visitors could be independent from the physical location. Nevertheless, the experiences presented in the descriptions of those projects were a valuable foundation for the implementation of our case study.

COSCH Case Study of the White Bastion: Description of Work

Interactive Digital Storytelling

Scholarly research and experience from various virtual cultural heritage applications show that storytelling needs to be incorporated in these presentations. However, there is still no universal methodology to tailor digital stories scenarios and no implementation which satisfies all the various categories of users.

Our research into digital storytelling for cultural heritage started with the virtual reconstruction of the church of the Holy Trinity in Mostar (Hulusić and Rizvić 2013). In this project we introduced a live storyteller telling stories about the church destroyed during the war in Bosnia and Herzegovina. He was recorded against a green screen and subsequently incorporated into an interactive 3D environment. We also implemented digital storytelling in our Isa bey's endowment project (Rizvić et al. 2014), where we virtually reconstructed destroyed objects

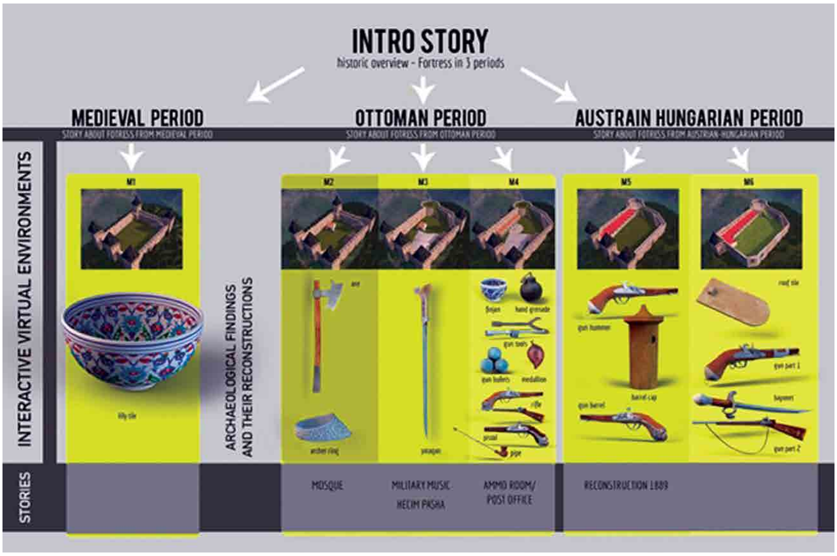


Figure 5.1. Structure of the virtual presentation. Screenshot of the White Bastion interactive application, 2016.

from one of the first endowments in the history of Sarajevo. The computer models of these objects and audio-stories were implemented in a single interactive virtual environment (IVE). The stories start when the user approaches a particular object within this environment. A part of that application consists of an interactive computer animation of a traditional dervish ritual, which used to be performed in one of the reconstructed buildings. A dervish is a member of one of many Muslim ascetic orders. Some perform whirling dances and ritual prayers in acts of ecstatic devotion. The user of the IVE is virtually placed in the middle of the ritual. He or she may select particular participants and objects, with a click, and start stories about them. This way we introduced interactivity in our storytelling, which proved to be attractive and engaging for the users. Interactive digital storytelling in various forms was also implemented in our Virtual Museum of Sarajevo Siege (Sarajevo Survival Tools) (Rizvić et al. 2012), where a digital story guides the visitor through the exhibition, as well as the Virtual Museum of the Bosnian Institute (Sljivo 2012), where the audio stories increase the immersion of the virtual visitor into the collection.

Another methodology to which we have arrived in the course of our research takes into account the present digital communication concepts. Users tend to watch movies for no longer than several minutes. They also like to have some idea of the structure presented in advance, such as the display within HTML pages which they are used to seeing. Therefore, we divided our story into units, or sub-stories, and offered the possibility of watching them on demand, after the user

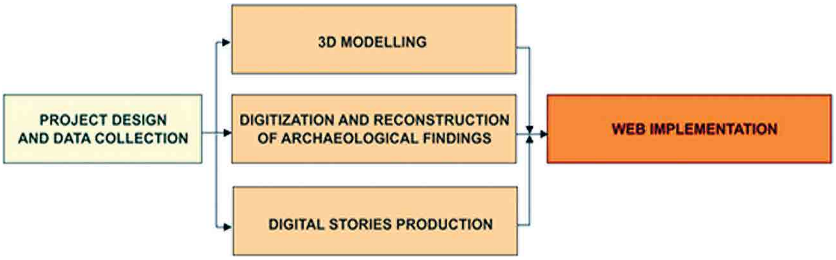


Figure 5.2. The 4D virtual presentation of the White Bastion project workflow.

is introduced to the content of the story. This concept was implemented into our Taslihan project (Rizvić and Prazina 2015). The project presented the largest inn in Sarajevo during the Ottoman period, of which only one wall is still standing. The project was implemented in three forms: a documentary, an interactive digital story, and a serious game. The final two implementations are sets of interconnected sub-stories and the interactive 3D model of the object.

In the White Bastion project we created a different combination of digital stories and interactive 3D environments. The structure of the project is shown in figure 5.1. The introductory story presents an overview of the site's history. The stories about medieval, Ottoman and Austro-Hungarian periods give more details of the site's transformation during these historic periods. There are also six interactive models of different phases of the fortress, with digital stories about particular objects, events, and characters from its history. There are also reconstructions of archaeological findings from the site.

This concept extends the work of the Taslihan project. Two kinds of navigation are available in both projects: from a story to the IVE, and from the IVE to the story. Our goal was to explore how users perceive these forms of communication, and whether they improve the user's immersion in the history of the cultural monument.

White Bastion Project

A 4D virtual presentation of the White Bastion was created with the aim to introduce the past of this important cultural monument to the general public through a visualization of its assumed appearances through history. Archaeologists and historians will also use this project as a foundation for their further research. The project was created by a multidisciplinary team of computer scientists, historians, archaeologists, writers, music composers, actors, translators, graphics designers, visual artists, and TV professionals. The project workflow is presented in a conceptual diagram (fig. 5.2).

Figure 5.3. Bijela tabija (White Bastion) fortress, Sarajevo, Bosnia and Herzegovina. Photo: Hakija Hadžalić, 2016.

The Site

The fortification known as the White Bastion is one of the most impressive and important historical sites in Sarajevo. It is located on the southeast outskirts of the city and offers a view over the city valley (fig. 5.3). Historically, it had a very significant and strategic position, being a part of the dominant defensive walls surrounding the old city of Vratnik, the oldest part of today's Sarajevo.

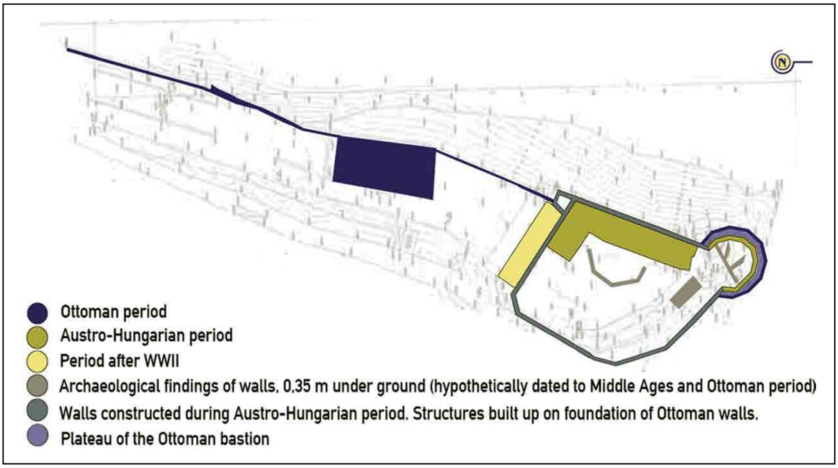


Figure 5.4. Actual state of the complex showing historical stratification. © Institute for the Protection of Cultural-historical and Natural Heritage of Canton Sarajevo, 2013.

Figure 5.5. Artefacts found on site. Photo: Museum of Sarajevo, 2000.

The significance of this historic site was manifested throughout history in various strata, starting from the medieval period until the present time. During archaeological excavations the remains of a fourteenth-century medieval fortification were found, as well as those from the Ottoman period in the seventeenth century, when the fortification was expanded and some new structures were built. During the Austro-Hungarian occupation of 1878–1918 a part of the fortification, including the mosque and some other structures within the walls, were demolished and replaced by new builds. During the early excavation (fig. 5.4), a significant number of artefacts were found (fig. 5.5), recorded, and conserved for an exhibition held by the Museum of Sarajevo.

Project Design and Data Collection

The project is designed as a collection of interlinked digital stories, IVEs, digitized archaeological findings, and their 3D reconstructions. The structure of this collection is shown in figure 5.1. Users are first offered the opportunity to watch a story, which introduces the content of the project. The stories about the three periods in the fortress's history offer more information about the particular phases in the development of the site. Users can browse six interactive 3D models of the fortress and watch the associated stories. Inside these virtual environments they will also come across reconstructed archaeological artefacts, found on the site. Clicking on them will provide more information about their context and historical significance.

The archaeologist leading the White Bastion excavation has identified six different stages in the appearances of the fortress. We based our virtual models on his

Figure 5.6. Artistic drawing of Catarino Zeno, a traveller whose travelogue is the earliest known written record of the fortress. Screenshot from the White Bastion film. © BHRT, 2016.

sketches and other input. For dimensions we used the excavation data and blueprints. The aim of the project was to raise the general public's awareness of the site. Therefore we have not implemented any modelling of uncertainty (showing with different colours or materials parts of the model according to the certainty of their appearance, so the assumptions are clearly visible). The scenario for digital stories was written by a professional novelist. He was using historic documents and sources to create the narrative. In order to increase the user's engagement in the stories he introduced a narrator. He chose for this character an eternal soldier from the fortress, who starts every sub-story with the words: "I am the soldier of Sarajevo, a prisoner of time, abandoned by death and transience." This character was introduced because we received very positive experience and user feedback concerning the digital stories told by a fictional character in the Taslihan project (Rizvić and Prazina 2015). The users said that the stories enhanced the experience of immersion and empathy with the character. We selected a professional actor to play the role of the soldier. He changed into different historic costumes, depending on the period depicted in the stories. Other characters mentioned in the stories were presented using animated drawings (fig. 5.6), as they are persons drawn from historical sources and their appearance is unknown.

3D Modelling

The first step in the modelling process was to build the terrain. In order to create a precise terrain model, the Digital Elevation Model (DEM) of the Balkans area, from

Figure 5.7. Computer 3D models of the exterior and interior of the medieval fortress. Screenshots of the White Bastion interactive application, 2016.

Figure 5.8. First 3D model of the fortress in the Ottoman period. Screenshots of the White Bastion interactive application, 2016.

the European Commission's GMES RDA project (2013) was reused. This geotiff map was then imported into Global Mapper, that is, a GIS application for reading and conversion of different spatial data sets. The precise terrain for the Sarajevo area was extracted from the map and exported as a 3D VRML file, which was then used in Cinema 4D.

Three-dimensional models of the White Bastion were created in Cinema 4D and Adobe Photoshop was used for creating and adjusting the textures. Six final 3D models correspond to the six different construction phases. The first one was in the medieval period, the second, third, and fourth in the Ottoman period, and the fifth and sixth in the Austro-Hungarian period. In order to achieve photo-realism of the renderings of the Bastion, the landscape with vegetation and the Miljacka river were added, and rendered to a high quality (figs. 5.7 and 5.8).

Digitization and Reconstruction of Archaeological Findings

Archaeological findings from the White Bastion site are housed in the Museum of Sarajevo. Most of them are not on display for the visitors to see, as the Museum does not have enough exhibition space. Our project thereby benefits the museum by providing a virtual exhibition of these objects in 3D reconstruction. Many artefacts are found as fragments that do not resemble the object from which they

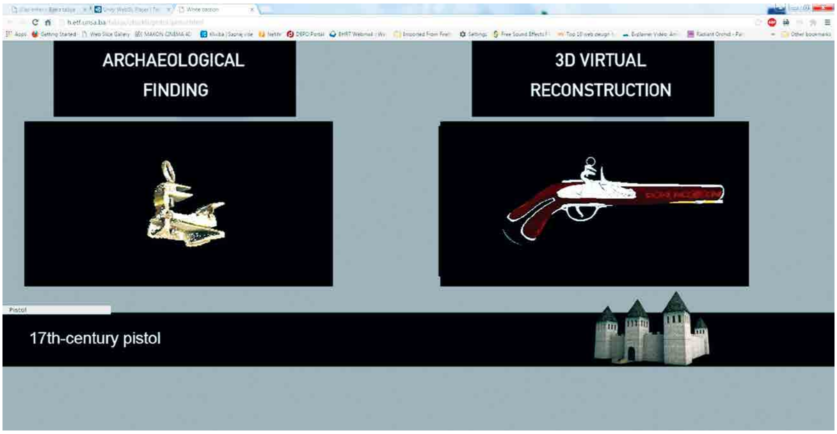


Figure 5.9. Display of an archaeological artefact and its virtual reconstruction. Screenshots of the White Bastion interactive application, 2016.

originate. 3D modelling is used to recreate the rest of the object. The users may click on the object's model, integrated in an IVE of the fortress (fig. 5.12) and open a screen, which shows both the digitized exhibit and its virtual reconstruction (fig. 5.9). Furthermore, the user can turn these objects around and interact with them in a way that is impossible in the physical museum.

We selected a group of twenty-two exhibits from all three historic periods of the fortress. The objects were digitized through photogrammetry. Thus, based on the acquired geometry, we reconstructed, in consultation with the expert archaeologist, the missing parts of each object to recreate its assumed original appearance.

Digital Stories Production

Digital stories were produced based on performance by a professional team from Bosnia Herzegovina Radio Television (BHRT). After the scenario and casting were finished, the director created a shooting guidebook as a reference for the whole TV crew. It included a detailed storyboard of all the stories with the text of narration, camera positions, and layouts of shots with visual effects. Graphics designers and visual artists created computer animations of different parts of the fortress and superimposed them onto the live footage of the fortress. They created computer animations of drawings of the characters whose appearance was not known. Computer animations of all six models of the fortress were designed and rendered according to the storyboard. The BHRT music production artists composed the original scores for the stories. They consist of different compositions for particular stories according to their topics. Shooting was performed in three locations

Figure 5.10. Location shooting of the story about the medieval period.

Figure 5.11. Location shooting of the story about the Ottoman period.
Photos: Selma Rizvić, 2016.

in and around the Bastion using a HD TV camera, location lighting, and sound equipment (figs. 5.10 and 5.11).

The voice-over narration was recorded in the sound studio by the actor and a radio speaker read the technical information about the fortress. After the editing, sound and picture post-production, eleven stories were finished: the introduction and final story, stories about the medieval, Ottoman and Austro-Hungarian periods, the mosque, Hecimoglu Ali Pasha, the ammo room/post office, military music, and the reconstruction of the fortress in 1899.

Web Implementation

All the 3D models were exported from Cinema 4D to fbx format and imported into Unity 3D for illumination and scenes creation. We set up three cameras for each fortress model, but only the virtual camera placed inside the object provides the user with the possibility to browse around. The models of reconstructed archaeological findings were imported into the scenes and placed on a table inside the fortress. The users can click on them and open the reconstruction interface. As some of the interactive environments contain digital stories, we linked the story files to cut-out silhouettes of the soldier to be clicked for playing the stories. The user's view of the said objects and triggers is displayed in figure 5.12.

Figure 5.12. Reconstructed artefacts and the trigger for a digital story inside the White Bastion interactive virtual environment. Screenshot of the White Bastion interactive application, 2016.

Figure 5.13. Home page of the White Bastion project website with interactive animation, 2016.

With all the elements prepared, the scenes were exported from Unity 3D into the WebGL interactive format. The website of the project was created in WordPress. The home page contains an interactive animation of all the phases in the development of the Bastion which can be seen by moving the mouse cursor (fig. 5.13). From there the users can enter the page with the structure layout (fig. 5.1) and choose desired stories and/or IVEs (White Bastion/Bijela tabija website).

Critical Discussion and Evaluation of Research

We believe that the most relevant evaluation of virtual cultural heritage applications should come from the users. Our projects are intended for the general public and aim to revive and implant cultural heritage objects and sites into the collective memory of people. We aim therefore to satisfy all users. Our study of the users' experience evaluation was conducted according to the principles of qualitative user experience methodology.

Experiment Design

At this point we have performed only an initial study of the users' experience evaluation. We selected a group of twelve users: eight from Bosnia and Herzegovina and four non-Bosnians. Three of them were under twenty-five, seven between twenty-six and fifty, and two over fifty years old. One reported poor computer literacy, six medium literacy, and five declared themselves expert computer users. Six of them sometimes play computer games, four of them do not, and two are regular gamers. Seven of the users visit museums occasionally and five are regular museum visitors. Their expertise differed. Some were computer scientists, some cultural heritage professionals, some language professors, and students of various disciplines. The Bosnian users were all from Sarajevo, so they could have had some prior knowledge about the object. Non-Bosnian users had no such knowledge.

The users were requested to visit the website of the project, explore its content and then fill out an online survey questionnaire. The questions in the user evaluation survey covered the following topics, which represented the objectives of our evaluation:

- User personal data (to identify to what target group the user belonged);

- Information perception (to find out how much users learned about the White Bastion from our application);
  - Q 1.1. When did you hear about White Bastion for the first time?
  - Q 1.2. From which historical periods originate remains at White Bastion's site?
  - Q 1.3. How many fortresses existed around the Old city of Vratnik?
  - Q 1.4. What was placed during the Ottoman period in the gunpowder magazine building?
- Interactive digital storytelling (to evaluate our concept);
  - Q 2.1. Which digital stories have you seen?
  - Q 2.2. On a scale from 1 to 10, how interesting and engaging did you find the stories?
  - Q 2.2.1. [if 9 or lower was chosen:] What would make it a "10"?
  - Q 2.3. On a scale from 1 to 10, how would you qualify the narrative?
  - Q 2.3.1. [if 9 or lower was chosen:] What would make it a "10"?
  - Q 2.4. On a scale from 1 to 10, how would you qualify the soldier character in the stories?
  - Q 2.4.1. [if 9 or lower was chosen:] What would make it a "10"?
  - Q 2.5. On a scale from 1 to 10, how would you qualify the music in the stories?
  - Q 2.6. On a scale from 1 to 10, how would you qualify the graphics (animated drawings) in the stories?
  - Q 2.7. On a scale from 1 to 10, how would you qualify computer animation in the stories?

Q 2.8. Is there anything you did NOT like in the stories?

Q 2.8.1. If yes, please describe what.

- IVEs (to establish the quality of presentation, navigation, and interaction; to discover if our triggers for inside stories and reconstructions of archaeological findings were intuitive enough for the users to find and explore this content);

Q 3.3. What aspect(s) of 3D models did you like the best?

Possible answers:

geometry

illumination

Q 3.3.1. [add if not mentioned]

Q 3.4. What do you think about the navigation through the models?

Q 3.5. Have you seen digital stories inside some models?

Q 3.6. Was it easy to find them?

Q 3.7. Have you explored models of digitized and reconstructed archaeological findings?

Q 3.8. Was it easy to find them?

Q 3.9. On a scale from 1 to 10, how would you qualify the presentation of digitized and reconstructed archaeological findings?

Q 3.9.1. [if 9 or lower was chosen:] What would make it a "10"?

- Overall user satisfaction (to identify where in development of the application we succeeded and where we have failed);

Q 4.1. On a scale from 1 to 10, how would you qualify the White Bastion application?

Q 4.1.1. [if 9 or lower was chosen:] What would make it a "10"?

Q 4.2. Did you feel immersion in the past of White Bastion?

Q 4.3. What do you think about the combination of digital stories and interactive 3D models?

Q 4.4. Should all stories have been inside models?

Q 4.5. Would you prefer this kind of presentation over a documentary movie?

Q 4.5.1. If yes, please describe why

Q 4.6. What did you like the best in the White Bastion application?

Q 4.7. What did you not like, or think could be corrected?

Results

The qualitative user experience evaluation methodology we used in our user study consists of the following steps. Firstly, the hypotheses which needed to be proved by the research are defined. Then the users are interviewed or asked to fill out questionnaires and provide relevant information. Their answers are coded and analysed in order to prove the previously defined hypotheses. In this user study we established the following hypotheses:

H1: Users learn about cultural heritage objects from virtual cultural heritage presentations.

H2: Through interactive virtual cultural heritage presentations users feel immersed in the past.

H3: Users prefer interactive cultural heritage presentations over documentary films.

In the information perception section of the user study we asked some questions from White Bastion's history about topics mentioned in the stories. Out of three questions we asked, two of them were answered correctly in almost 100 per cent in the case of Bosnian users (only one answer was wrong), while the third question was answered incorrectly by 62.5 per cent of users. The reason for this could have been the fact that they did not watch the corresponding story, which was available within the virtual environment. The answers to one question from this section by the non-Bosnian users were 100 per cent correct and only one of them did not answer correctly the remaining two questions. From these results we can conclude that our hypothesis H1 has been proven.

At the beginning of the evaluation of our interactive digital storytelling concept we investigated how many digital stories users have watched. We divided the stories into two groups, according to their position in the interactive project structure (fig. 5.1):

S1: stories with direct access (intro, three stories about time periods in the history of the fortress, and the end story);

S2: stories placed inside IVEs (the mosque, Hecimoglu Ali Pasha, the ammo room/post office, military music, and reconstruction of the fortress in 1899).

All the Bosnian users watched the introductory story and all but one watched stories about all three periods in the fortress's history. The stories from the S2 group were seen by approximately half of the users. Four out of eight users watched the end story. Three out of eight users reported that it was not easy to find stories in

IVEs. The non-Bosnian users watched three stories about time periods; two out of four watched the introductory story and none of them watched stories from the S2 group. We believe that the reason for not watching S2 stories was that they could not find them, meaning that our soldier-trigger was not intuitive enough. Only three out of twelve users think that all stories should have been placed inside IVEs. Regardless, the users marked the stories very highly (ten out of twelve users gave them 10 on a scale from 1 to 10). All users found them interesting and engaging. The soldier character was the most appreciated element in the stories.

An evaluation of IVEs shows that all Bosnian and three out of four non-Bosnian users explored them. The majority of users appreciated their appearance. Six out of twelve had no problems with navigation, while five reported some problems. One user could not open them at all. In general, the IVEs of the Bastion models are slow to load (about five minutes when using a good Internet connection). We need to address this problem through the optimization of their geometry. Another problem is that they do not work well on mobile platforms and so we are looking for the best solution to this. Regarding the archaeological findings and their reconstructions, seven out of twelve users succeeded in finding and exploring them in the IVEs, while five users have not. Those who found them expressed their appreciation with the highest mark.

Eleven out of twelve users reported that they felt immersed in the past, which confirms our hypothesis H2. One of the most important questions for us in the user evaluation was whether the interactive virtual cultural heritage presentation is preferred over a sequential presentation in the form of a documentary. Ten out of twelve users answered this question positively, which confirms our hypothesis H3. A number of users commented on some advantages and drawbacks of this approach. Most of them reported feeling more engaged and paying more attention in the interactive presentations. They appreciated the possibility of exploring the IVEs which they could not do in a film. They liked the combination of digital stories and models because "models are described by stories and can display the information from stories." Two users noted that in this kind of presentation information is scattered and they cannot be sure they did not miss something. They preferred to be offered a tailored story than to create it themselves through interaction.

Future Research and Conclusion

In this chapter we have presented a new concept of interactive virtual cultural heritage presentation, consisting of a combination of digital storytelling and IVEs. We can conclude that this form of presentation is more attractive and engaging for the majority of users who feel immersed in the past and gain more information about the presented site and its history. Digital storytelling needs to be carefully designed and the introduction of one or more characters is highly appreciated. The projects need to be implemented by multidisciplinary teams of professionals, with particular emphasis on graphics design and visual arts, as the visitors find these elements most attractive.

A lot of work still remains to be done in devising a concept appreciated by *all* target user groups. From the results of the evaluation survey we could see there are still some users who prefer traditional forms of communication. Some problems with navigation in IVEs need to be solved to attract more users to interactive presentations. We still need to research what the ideal duration of individual story units should be and how they should be interconnected between each other, and with IVEs.

However, we believe that the time is ripe for these forms of communication. We need to work to help users to perceive cultural heritage in the same way they perceive millions of online bits of information, bombarding them every day. Digital technologies and storytelling are thus powerful tools to help implement the perennial idea of travelling to the past.

Chapter 6

DIGITIZATION OF CULTURAL HERITAGE AT THE NATIONAL MUSEUM OF ROMANIAN HISTORY, BUCHAREST

IRINA MIHAELA CIORTAN

ABSTRACT

The National Museum of Romanian History in Bucharest holds a vast number of archaeological objects of both Romanian and European cultural significance: ceramics, objects made of marble, stone, copper, gold, and silver, as well as a collection of painted icons and manuscripts, dating from prehistoric periods to the Modern Age. The museum has been undergoing renovation for several years and the majority of the objects in its collection are not available to the public.

The main purpose of the case study described in this chapter is to grow the collection of digitized objects and their 3D visualizations, and to present these for viewing in a virtual gallery. Through this the general public, as well as scholars, will be able to access virtual surrogates of the objects that are at present not available on site. Another objective of this case study was to implement state-of-the-art non-invasive techniques for acquiring images of the artefacts, using both spectral and spatial object documentation. Finally, the case study aims to disseminate information about the digitization process and to provide specifications and guidelines of good practice that will serve both the scientific and arts and humanities communities involved in the field of cultural heritage. The objects used in this study were: three ceramic vases from the Cucuteni culture, three icons painted on wood, and a collection of medieval manuscripts. The techniques used for recording and analysis were photogrammetry and multispectral imaging.

Keywords: icons, medieval manuscripts, Cucuteni, photogrammetry, multispectral imaging, COSCH

Introduction

If one were to think of cultural heritage as a person, one would most probably describe this person as a wise, long-distance time-voyager, who survived and withstood centuries of history in order to be able now to share a self-defining life story; a person whose eyes sparkle with the desire of surviving twice as many centuries longer to keep the story mimetically close to its original: alive, intact, and unperturbed. For the story may be looked upon as one of the substantial means through which one can reach the true understanding of an instance. The time-voyager, the embodied cultural heritage, is aware that the greatest threat to his story is the loss of credibility, which may happen easily when change is waiting at the corner, year after year. Thus, the most urgent need of cultural heritage is its confrontation with time; the immediately triggered change is, first and foremost, the need for documentation as a stable proof against uncertainty. Once documentation has been secured, further needs such as conservation, preservation, and restoration are easier to pursue since the description of the original is archived, with as much detail and accuracy as possible. The more continuous the set of finite moments across the axis of history that the spotlight is shed onto a cultural heritage instance, the less darkness we (the curators, archaeologists, and conservation scientists) will have to fathom when later posed with the problem of gathering full knowledge about the history of the instance.

However, cultural heritage is not a stand-alone entity and there are many stakeholders involved, with many categories of end-users with both different and common needs. The best way to discover and tackle these needs is by the most ancient tool of research, that is, asking questions. Through an intensive questioning process and conversations with the stakeholders interested in cultural heritage, needs arise and can afterwards be collected and classified according

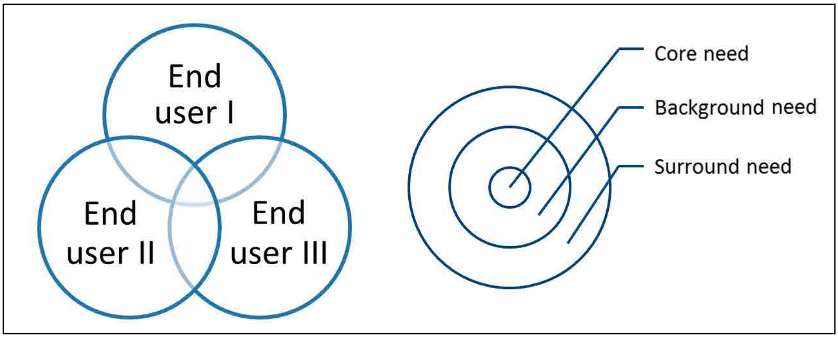


Figure 6.1. Pattern of end-user needs in the planning phase of a cultural heritage project. Left: Venn-like pattern, Right: Concentric pattern. © Irina Mihaela Ciortan, 2016.

to their similarity. From the experience of the current case study, the inquiring process that leads to the discovery of needs can follow two patterns: a Venn-like pattern or a concentric pattern (fig. 6.1). The former implies various groups of end-users, who in the diversity of their discourse have an underlying, intersecting common need, while the latter consists of needs depending on external factors, built around an essential core.

When starting a cultural heritage project, the first imagination exercise is to envision the large picture, that is, to see the starting point and the far end, to jump from A to Z, without drawing all the important letters in between. The rough sketch of the large picture helps in finding and then pursuing a common, holistic goal that will govern the subsequent, deterministic steps.

The Context of the Case Study (Problem Statement)

The National Museum of Romanian History (NMRH) holds vast collections of cultural heritage items relevant to the history and culture of Romania. They are housed in a nineteenth-century neoclassical palace, originally the central Post Office, on one of the oldest streets in the historic centre of Bucharest. The museum is currently (2016) undergoing renovation work, meaning that the objects are not accessible to visitors. Hence, this is how the first research questions were raised: How to support the general public interested in the museum during the renovation? How to give conservation scientists access to the objects? How to stimulate interest in the museum? How to enhance the virtual gallery of the museum?

Then, the question that followed naturally was: How to select representative objects for digitization? The choice of objects that would showcase the diversity of the NMRH's collections was deliberated in collaboration with the museum curators, followed by a conversation about the historic significance of objects, as well as their condition and conservation requirements that may impact on advanced documentation. Given these criteria, the artefacts chosen for the present case study were Orthodox icons, ceramic vases from Cucuteni culture (Ellis 1984), and medieval manuscripts. The chosen artefacts were documented in the museum archive as 2D images only (see Table 6.1 for details of the selected objects).

Having identified the core need—documentation—and having chosen representative cultural heritage objects, the next questions concerned the technologies, techniques, and tools that could be used to achieve accurate documentation, and subsequently the display of the visualization in a virtual gallery, so as to meet expectations of the remote visitors. Is 3D digitization necessary? Are we interested in gathering more information about the material or spectral characteristics? Should we confine our study to an already trodden path or should we explore novelty? It was also necessary to identify the goals of the virtual exhibition. Should it only inform? Or should it, perhaps, tangentially include education and learning objectives? All these topics will be covered below.

State-of-the-Art

Documentation is one of the most important and urgent tasks for cultural heritage (Yilmaz et al. 2007), especially if assuming hypothetical natural catastrophes that could provoke loss (Patias 2006), as was the case in the series of earthquakes in Italy in 2016 (ICCROM 2016). One way of classifying the plethora of documentation techniques in the literature is to divide them according to the appearance attributes that they are primarily intended to record. Thus, we will further use *spatial techniques* to refer to the collection of technologies that are optimally designed to capture the shape and geometry of an object, while *spectral techniques* designate the set of imaging systems that are developed to record accurate and precise information about the reflectance behaviour of an object as a function of wavelength.

Pavlidis et al. (2007) offer a comprehensive review of state-of-the-art technologies used to capture the 3D geometry for cultural heritage applications, that can be roughly divided between laser scanning techniques and a group of "shape recovered from ~" methods, where ~ may stand for structured light, motion, silhouette, texture, shading, stereo, etc. Remondino and El-Hakim (2006) classify the image-based 3D modelling techniques and highlight the advantages of close-range photogrammetry. They point out a series of guidelines for improving the photogrammetric acquisition and the quality of images acquired, so that the 3D reconstruction is less prone to errors and more precise.

Spectral imaging has already made a name for itself in cultural heritage projects (Stanco et al. 2011), as the spectral signature can be considered a definitive characteristic of the object. It has been used for pigment mapping (Deborah et al. 2014; Zhao 2008), crack detection in paintings (Deborah et al. 2015), and manuscript analysis (Ciortan et al. 2015). The greatest advantage of spectral imaging in comparison with alternative technologies for capturing reflectance information, as for example spectroscopic measurements, is that instead of sampling the recorded reflectance for a restricted contact area, it captures a 2D image array with a reflectance measurement at each pixel. However, the reflectance information may be more discrete or more continuous depending on the bandwidth of the system, which differentiates the multispectral imaging systems (up to 30 bands) from the hyperspectral systems (30 bands onwards). The equipment cost increases with resolution in either the spatial or spectral domain. Usually, a trade-off is the solution between extended accuracy in one of the two domains and the decision depends on the characteristics of the acquired object such as size, flatness and material composition.

Although when treated individually, the spectral and spatial domains have been well explored, it is difficult to locate previous experiments and technologies that approach a spectro-spatial setup. This is not surprising, given that the task is far from trivial. The field that opened the gates to a registered fusion between data with resolution in spectral and spatial domain is represented by spectral imaging systems, with their variants: multispectral and hyperspectral imaging systems. Spectral imaging systems output aligned images on the x and y dimensions along the sampled electromagnetic spectrum (the frequency of sampling determines the resolution in the spectral dimension). Limited even in the x and y dimensions, spectral imaging systems have a substantial lack of information in the z dimension, making depth information recovery and hence a so-called multi/hyperspectral 3D model a very difficult task to solve. Another serious limitation is the inter-band detail variation captured by the hyperspectral images and related to changing reflectance properties, where one detail might be visible for one wavelength and then disappear in another, which is challenging when aiming to reconstruct 3D information from the whole. Shy attempts have been made in this direction, culminating with an approach (Zia et al. 2015), where 3D information is extracted band-wise and is recomposed for the whole hyperspectral data set, based on a structural descriptor, used for the spatial registration between the single-wavelength point map and then registered with a complete three-dimensional model.

Considering the features of the objects involved in this case study, both spatial and spectral recording techniques were involved as follows: the defining intrinsic feature of the ceramic vases is their shape and geometry, so spatial documentation was performed. However, it is worth remarking that the Cucuteni ceramic vases are unique for their colour patterns, so precise and accurate colour information might also present relevant research material, which leads to exploring combined 3D multispectral reconstruction. For the icons and medieval manuscripts, where the geometry is rather flat above microscale, but the colour and reflectance properties carry more importance in documenting the appearance of the objects, multispectral techniques were considered as appropriate to explore.

Description of Work

The case study encapsulated both the spatial documentation with photogrammetry of the Cucuteni ceramic vases, and the spectral documentation with a filter-wheel digital camera of three Orthodox icons, together with a collection of medieval manuscripts. In this section, the acquisition campaign will be described and the pros and cons of each technique discussed.

Spatial Documentation

The technique chosen for spatial documentation was photogrammetry due to the versatility of the output data, the relative low-key requirements of the set-up (digital camera, light sources, rotating table, calibration target), and the ready availability of post-processing software. Recent technological advances in digital cameras, computer processors, and computational techniques make photogrammetry a portable and powerful technique. This enables a dense and precise 3D surface to be constructed from a limited number of photos, captured with standard digital photography equipment, in a relatively short period of time and with low-costs. One disadvantage is that the automation of the post-processing software gives little control over the final product. However, additional editing of the 3D photogrammetric data, such as smoothing or hole filling, can be performed by additional software

In the present case study, the setup used to acquire photogrammetry data consisted of a digital camera Sony NEX 6, with 16–50 mm f/3.5–5.6 lens, two Studioflash 1000 w lights, a white panel for diffusing the light, and a rotating table (fig. 6.2). For each object placed on the turntable, thirty-six images were taken, at intervals of ten degrees. The resulting image stack was post-processed in Photoshop (masking the region of interest corresponding to the object and discarding the remainder in order to decrease computation time) and afterwards, the 3D models were generated with the AgiSoft PhotoScan software, which implements the Structure from Motion algorithm.

Figure 6.2. Setup for photogrammetric acquisition of the ceramic vases. © National Museum of Romanian History, Bucharest, 2015.

Spectral Documentation

The spectral documentation was performed by a SpectroCam filter-wheel multispectral camera that allows for the capture of 8-band registered images. The camera incorporates an InGAas sensor for increased sensitivity with 15 µm pixel size, with a full-frame pixel resolution of 640 × 512 (width × height). The advantages of this setup are the relatively low costs compared to other multispectral setups, the possibility to attach additional filters with different spectral transmittance (for acquisition in the NIR and UV ranges) and the increased portability, making it appropriate for *in situ* acquisition. The disadvantage is that the change of a new set of filters might cause a misalignment from the images acquired with a previous set of filters. The SpectroCam camera comes with built-in software for real-time visualization, and the multispectral images are output in all common file formats (raw, jpg, bmp, png) enabling post-processing with tools such as Matlab (proprietary) or ImageJ (open source).

There is no constraint regarding the orientation of the setup, hence the cultural heritage object can be arranged either vertically or horizontally, depending on the space limits given by the acquisition site. In the campaign conducted for this study, the camera was positioned parallel to the horizontal acquisition scene and the light source at the same close distance as the camera distance, on the side (fig. 6.3). Apart from the object, the acquisition scene included a perfect white diffuser (Spectralon target), necessary to compensate in post-processing for the non-uniformity of the illumination. The set of filters used for the documentation of the Visible Spectra had peak wavelengths at: 425, 475, 525, 570, 615, 680, 708, and 784 nm.

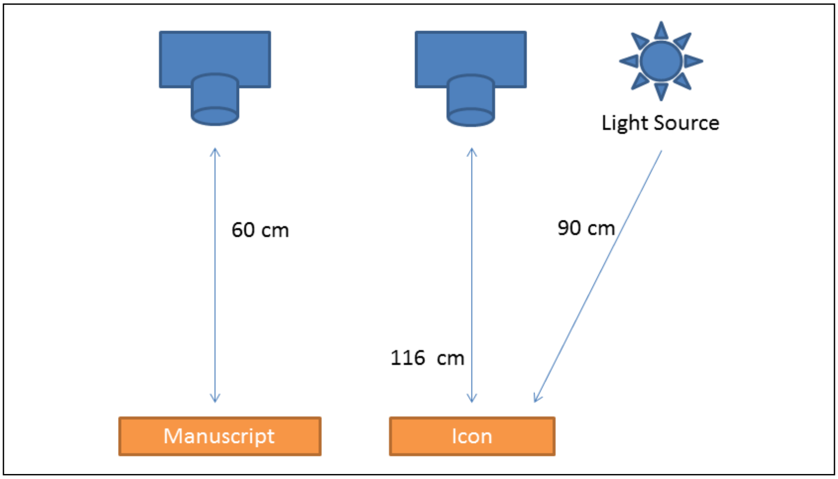


Figure 6.3. Setup for the multispectral acquisition with the filter-wheel camera of the manuscripts and icons. © Sony George, 2015.

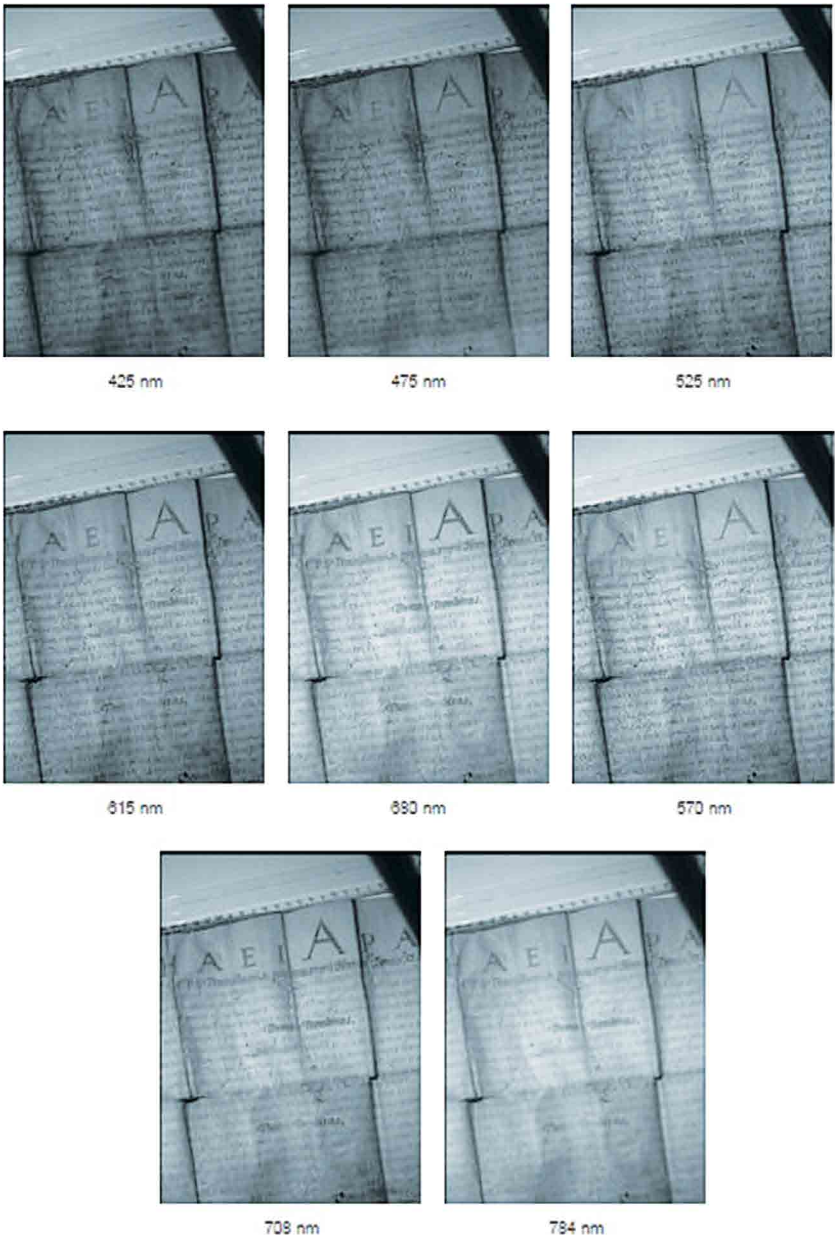


Figure 6.4. The single-band images corresponding to each of the eight filters. Note how some of the text begins to fade as the wavelength approaches the NIR. Photo: Irina Mihaela Ciortan.

Visualization and Virtual Gallery

The documentation process results were uploaded to a virtual gallery dedicated to this case study at http://romanianculturalheritage.omeka.net/about (work in progress). The virtual gallery was built on the Omeka.net Platform, which is especially designed for the archiving of cultural heritage items, including the metadata fields defined by the Dublin Core System.

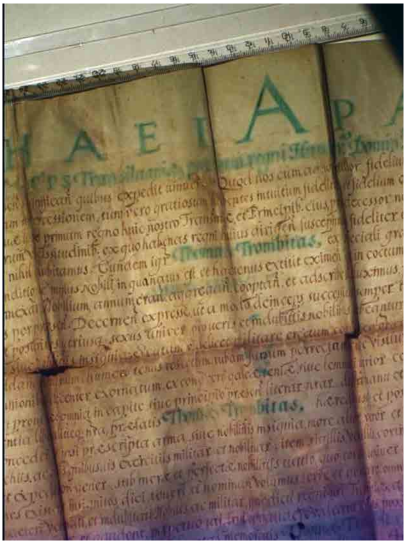
Multispectral data enable multiple visualizations. The display of single-band (Padoan et al. 2008) image series shows how the imaged artefact changes its reflectance with wavelength (fig. 6.4). A traditional RGB image can be simulated by merging three monochrome images that correspond to the spectral bands with the highest signal for RGB colours (fig. 6.5). From the current set of filters, the association was: R-680nm, G-570nm, B-475nm. If NIR have been used, false-colour visualization (Douma 2008) would also have been possible, by assigning the Red channel to the NIR information, Green to Red, and Blue to Green. Similarly, if UV filters had been used, the shift of the channels for generating a false-colour image would have been: Blue for the UV information, Green for the Blue information, and Red for the Green information.

Evaluation of Research

This case study enabled multispectral image documentation for museum objects, adding information and visual quality to the museum virtual gallery. While quantitative evaluation has always been a challenge in cultural heritage, either due to the lack of ground truth or to the difficulty of fair comparison between the data, qualitative evaluation and visual assessment offer a more immediate and spontaneous feedback. Out of the interdisciplinary discussion about carrying out the acquisition, a common criterion was agreed between the parties: novelty. It might be novelty regarding the perspective from which the cultural heritage artefact is seen, novelty of the acquisition technique and its implementation, or novelty triggered by new findings in the nature/material of the object that previous techniques have not revealed. In cultural heritage tasks, whether documentation, conservation, or restoration, a toolbox of complementary technologies is needed for viewing the object from multiple perspectives, as this is the path to reveal its full authenticity.

A case study, as any research experiment, uses one method to find its results and to assess the appropriateness of the results to the initial purpose. The method may provide novel results, the same results in comparison to previous techniques, or it may provide data that are difficult to interpret meaningfully for the given input. Nonetheless, by exploring the particular method, future research can be continued or not in that direction, depending on how encouraging the results are.

Figure 6.5. The RGB visualizations of the Orthodox icons and the medieval manuscripts in the National Museum of Romanian History, Bucharest. Photos: Irina Mihaela Ciortan.



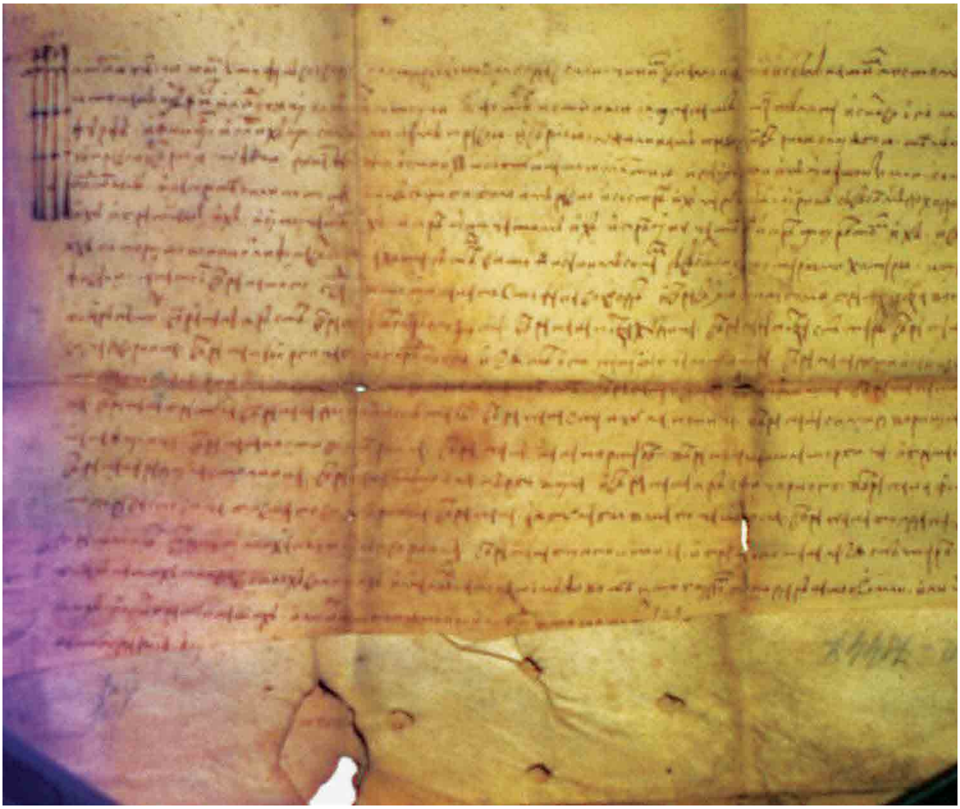


Table 6.1. Selected Cultural Heritage Objects, as Documented in the Database of the National Museum of Romanian History, Bucharest.

Inventory No.	Subject	Creator and dating
88220	Saint Michael and Saint Gabriel	Artist unknown, last quarter of the 18th century
88232	Virgin Mary and Child	Unknown Russian artist, nineteenth century
172399	Crucifixion	Unknown artist, eighteenth century
12143	n/a	Object belonging to the Neolithic Cucuteni culture; dating imprecise
12136	n/a	Object belonging to the Neolithic Cucuteni culture; dating imprecise
15894	n/a	Object belonging to the Neolithic Cucuteni culture, approx. 3800–3600 BC
MS 30414	n/a	Mihail Apafi, Prince of Transylvania, Sibiu, 1663
MS 107427	n/a	Stephen the Great, 1462
MS 108160	n/a	Voievod Ștefan Lupu, 11 May 1660
MS 108162	n/a	Radu Mihnea, 26 March 1618
MS 75447	n/a	Ștefan II, Voievod of Moldavia, 16 April 1443
MS 131443	*Pravila de la Govora* (Law book of Govora)	The first Romanian Code of Laws published in Wallachia, 1640, under the rule of the voivod Matei Basarab; in vernacular Romanian, in Cyrillic alphabet

In conclusion, this case study at the National Museum of Romanian History provided spectral and spatial documentation for a number of cultural heritage objects, recording one moment in their history and status, offering a new perspective for visualizing appearance features and setting a new benchmark for future research, as more and more technologies emerge to be used for the recording of cultural heritage.

Object type and main material	Details and dimensions
Icon on wood panel	Double-sided icon, 26.5 × 21.5 × 2.4 cm
Icon on wood panel	Portable icon, 39.5 × 31.5 cm × 2.5 cm
Icon on wood panel	The icon was restored in the 2010s. 38.0 × 31.2 × 2.5 cm
Ceramic vessel	The vessel was made of clay, decorated with painted circular and spiral designs, and fired
Ceramic vessel	The vessel was made of clay, decorated with painted circular and spiral designs and fired
Amphora with bitronconic decoration	The vessel was made of clay, decorated with intricate designs and fired. Height 36.0 cm; max. external diameter 38.0 cm; internal diameter 17.2 cm
Manuscript on parchment, written with sepia and green inks; red wax seal, silk threads, wood	Document issued by Prince Mihail Apafi bestowing a noble rank and coat of arms on Toma Trambitas of Betlean. 32 × 61cm; seal diameter 7cm
Manuscript with attached seal	31.0 × 52.5 cm
Manuscript charter with attached seal	49 × 64 cm
Document with attached seal	44.5 × 70.0 cm
Manuscript in ferrogalic ink on parchment	The document, 21 × 27 cm, is written in Slavonic.
Codex printed in typographic ink on paper. The cover is made of cardboard and is wrapped in leather	The codex, 19.7 × 14.0 × 3.5 cm, consists of 337 pages. It was restored in 2010 and subsequently scanned in 2D though the programme “Manuscriptum.” The codex is being preserved wrapped in Japanese tissue, with neutral pH and cased in antistatic and fireproof polyethylene foam.

Chapter 7

BREMEN COG: THREE RECORDING TECHNIQUES FOR ONE OBJECT

AMANDINE COLSON and LEVENTE TAMAS

ABSTRACT

The Bremen Cog is a ship which was discovered in the river Weser close to the city of Bremen in 1962. Based on dendrochronological examination, the cog was built in 1380. It was successfully conserved and restored with polyethylene glycol (PEG) at the German Maritime Museum in Bremerhaven and has been on display since 2000.

Despite its age, the cog was well preserved and the steerboard side was almost complete. The reconstruction of the missing parts seemed therefore possible and of interest to the public.

The museum wanted to give a new lease of life to the cog and allow the public to see it from different viewpoints, while also communicating research results. The case study described in this chapter focuses on the three-dimensional monitoring of the ship's current condition, the understanding of wood deformation that occurred in the past, and preventing future changes. Another objective was to make a 3D computer model, based on the same digital data, for the participatory education of the public. This model of the ship will enable its continued public presentation, through a virtual surrogate, during the building works. The case study involved different tests: photogrammetry and Structure from Motion acquisition, 3D scanning and total station. Data analyses were also carried out.

Keywords: Deformation monitoring, large-scale objects, conservation, restoration, laser scanning, total station theodolite, photogrammetry, COSCH

Introduction

The Bremen Cog was discovered in 1962 near the city of Bremen, Northern Germany, in the river Weser. The decision was taken to salvage the ship. Most timbers, together with finds, were recovered from the river bed between 1962 and 1965. Thanks to dendrochronology analyses, the ship timbers were dated to the second half of the fourteenth century. Following a six year reconstruction at the purpose-built German Maritime Museum in Bremerhaven, the Bremen Cog was found to be 24 m long, 7 m wide and 4 m high. Its conservation took almost twenty years before it was possible to present the ship to the public in 2000. About a year later, the first signs of deformation occurred. After different trials to design a new support system for the ship, the museum decided to work on a system that would feed information to the future support girdle. At that point the relevance of designing a non-invasive, long-term deformation monitoring system became clear.

Our study of the Bremen Cog was aimed at testing different recording methods on a single large-scale object to gain an overview of the expertise and the resources necessary to perform the challenging deformation monitoring over time. The study was conducted as an activity of the network, Colour and Space in Cultural Heritage (COSCH). It focused on testing three different techniques in order to compare their feasibility for a future deformation monitoring system. The expertise available within COSCH offered an ideal opportunity to gain new knowledge and benefit from feedback from the scientific community. Three techniques were chosen: photogrammetry, laser scanning, and total station. The approach was to compare, analyse, and fuse the data, in order to assess the advantages and drawbacks of each technique. Another aspect of this research was concerned with museum education, looking at digital visualization as a means to present the ship to visitors during renovation of the Scharoun building, where the ship is on display.

Earlier Research

Definition

The term monitoring is widely used in a range of fields. According to the Oxford English Dictionary, the elementary meaning is, "To observe and check over *a period of time*, maintain regular surveillance over" (emphasis added). Irrespective of the field of study, time is the central notion. In the field of conservation, we commonly differentiate between two types of monitoring that differ in methodology and in principle: one is concerned with preventive conservation and the other with remedial conservation. The ICOM-CC defines preventive conservation as "all measures and actions aimed at avoiding and minimizing future deterioration or loss. . . . These measures and actions are indirect—they do not interfere with the materials and structures of the items. They do not modify their appearance." Remedial conservation involves, according to the same resolution, "all actions directly applied to an item or a group of items aimed at arresting current damaging processes or reinforcing their structure. These actions are only carried out when the items are in such a fragile condition or deteriorating at such a rate, that they could be lost in a relatively short time. These actions sometimes modify the appearance of the items" (ICOM-CC Resolution 2008). Therefore,

- passive monitoring concerns the environment, climate and humidity changes around the object, while
- active monitoring concerns the deformation and degradation processes of the object itself.

Monitoring in Conservation of Cultural Heritage

Since the 1980s, control and monitoring of temperature, relative humidity, and light conditions have been recommended by preventive conservation specialists (Thomson 1986, 85). Ideal levels have been established and modern data-loggers enable conservators to take climate measurements at defined intervals and save the data digitally in spreadsheets. However, data analysis and visualization remains a challenge. Moreover the comparison to other decisive factors, such as meteorological data or the number of visitors is required (Michalski 2010, 355–56).

Modern technologies have helped make significant advances in the documentation serving different disciplines, including archaeology, history of art, and biology. The last decade saw intensive digitization campaigns in museums throughout Europe, among others in natural science museums[1] and in archives. In terms of active monitoring, most conservators are documenting the conservation state of objects using traditional techniques, such as drawing, photography, description, and sampling. Although coherent, these methods deliver less accurate information and become problematic for large objects.

Other Comparable Projects

The Vasa Museum in Stockholm, Sweden, houses a 69 m long archaeological ship. Laser technology has been used since October 2000 to measure systematically the changes in shape (Jacobson 2003, 186–88). The system was designed by the School of Architecture and Built Environment, Department of Geodesy of the

1 For example, the digitization of insect specimens by the EoS project at the Museum für Naturkunde in Berlin, see http://eos.naturkundemuseum-berlin.de/ (accessed 20 December 2016).

Royal Institute of Technology. Measurements are taken by the technicians twice a year. Over 400 points are recorded using a total station. This type of laser-based electronic theodolite, also called tachymeter, is used in modern surveying and archaeology to measure distances. The 3D data are processed and transferred to a dedicated software platform for visualization and comparison of the results (Horemuž 2003, 5). Work is ongoing to analyse the data acquired over the last sixteen years (van Dijk et al. 2016, 109) which will assist with the construction of a new support system.

The Mary Rose Museum in Portsmouth, England, is planning the same procedure to measure the sixteenth-century flagship of King Henry VIII. The Mary Rose is 38 m long (Schofield et al. 2013, 399–400).

The recent digitization of the fifteenth-century merchant ship found in Newport, Wales, shows the advantage of digital documentation of archaeological wood for assessing the deformation before and after a conservation treatment (Jones 2015). A Faro-Arm, a portable coordinate measuring instrument, based on laser technology was used. In fact, noticeable changes were detected by comparing the three-dimensional data processed in the commercial software Rhinoceros.

Impact on the Research Community

The participation of the German Maritime Museum in the COST-Action TD1201, Colour and Space in Cultural Heritage (COSCH), enabled the authors to undertake new research of the Bremen Cog. The COSCH case study consisted of preliminary tests on this fourteenth-century ship using 3D laser scanning, total station, and photogrammetry as pertinent methods to monitor three-dimensional deformation processes (see part 2, Methods and Technologies, for further explanation).

In response to a growing interest in underwater archaeological finds of this kind in Europe, a working group was founded in France in 2015. The initiative came from the conservation laboratory, Arc Nucléart in Grenoble, which is involved in the conservation of many wooden archaeological ships in France. The group is called *Groupe d'Étude et de suivi des épaves restaurées* (GEISER) and is led by Marine Crouzet of A-CORROS, Arles. Its expert members gather to discuss preventive conservation of ships, on display in French museums, treated with polyethylene glycol. Monitoring the temperature and relative humidity are central to this scientific exchange, as well as deformation monitoring. Following the publication of information about her research into the Bremen Cog on the COSCH website, the co-author Amandine Colson was invited to participate in this working group.

COSCH Case Study of the Bremen Cog: Description of Work

Significance of the Object

Archaeological organic material (remains of plants or animals) survives in one of two extreme conditions: wet or dry (Cronyn 1990, 243). Under European latitudes, we mostly deal with damp or waterlogged objects, found underwater in the sea, lakes, or rivers, but also in marshes or swamps. Preservation of such material is a real challenge for conservators and means long conservation treatments, from a few weeks to several years. A treatment of large pieces of wood, or a larger ensemble such as a shipwreck, can take up to several decades. Few projects have been carried out on large collections of archaeological organic objects and large-scale objects. High cost, problematic storage, and display are the main barriers.

Figure 7.1. Bremen Cog shortly after the opening of the permanent exhibition in 2000. Photo © German Maritime Museum.

The size of shipwrecks varies from a river barge to warship. They are rarely found and each discovery causes a public sensation, as well as excitement among the specialist community. A handful of wooden ships have survived in Europe and are preserved and presented in museums. Apart from the already mentioned Vasa in Stockholm and the Mary Rose in Portsmouth, England, larger ships include the Oseberg and Gokstad in Oslo, Norway, and the Skuldelev ships in Roskilde, Denmark. Due to the rarity of finds, only a few specialists deal with the preservation of archaeological wood, which contributes to the singularity of the field.
The Bremen Cog (fig. 7.1) was found in October 1962 downstream from the city of Bremen, during enlargement work of the riverbed of the Weser, opposite the Europa Hafen (Pohl-Weber 1982, 16).

The significance of the discovery was quickly realized and the decision was taken to dismantle the ship on site, taking it apart as much as possible before the arrival of first ice of the winter of 1962–63 (Pohl-Weber 1982, 17). The salvage of most of the timbers took place by December 1962. A diving campaign was organized in the summer of 1963 and a systematic survey of the area was carried out in the summer of 1965. A diving bell covering 24 sq. m for each position was used. All in all twenty-three working days and 274 changing positions were necessary to cover a global surface of 1400 sq. m of the river bed (Pohl-Weber 1982, 23–24) and around 2000 finds were raised (Bardewyk 1982, 5). In 1969 some wood samples were analysed through dendrochronology and established the medieval dating: the wood used for building the ship was felled in 1378 (Klein 2003, 157).

After some time in storage, the timbers were transported during the summer of 1973 to the German Maritime Museum in Bremerhaven, then under construction (Lahn 1982, 32). The reconstruction of the ship was carried out under high humidity by a team of up to five people. In the spring of 1979 the Bremen Cog was standing (Lahn 1982, 29) ready for conservation, which has been ongoing ever since.

The conservation of waterlogged-wooden objects is a very delicate matter (Hoffmann 2013, 3). The main challenge is essentially to replace the water lodged in the cells with another substance that can provide a support for the cell walls when the water is gone (Hoffmann 2013, 39). Only then, the shape and the original surface can be preserved to ensure that the structure will not collapse during the drying process. In order to prevent drying, the object must remain submerged or in 100 per cent relative humidity during the entire process. Therefore, the water substitute must necessarily be water soluble (Hoffmann 2013, 4).

Only a few replacement agents fulfil these prerequisites. One of the most popular is polyethylene glycol (PEG), an organic compound also used in medical industry (Horie 2010, 188 and 192). It was used, with promising results, in the late 1950s to treat archaeological wood in Denmark and in Sweden (Hoffmann

2013, 44). Over the decades, it became the most widely used method for the conservation of waterlogged archaeological objects (Hoffmann 2013, 44).

The Bremen Cog and the five Skuldelev ships in Roskilde were both found in the same year, and a year after the warship Vasa in Stockholm (Hoffmann 2013, 44), which led the teams to work closely together and form an international working group, that was to become the ICOM-CC Wet Organic Archaeological Material group.

After the north German discovery, a group of experts from the University of Hamburg (Hoffmann 2013, 80), in collaboration with Danish and Swedish colleagues, proposed a long-term conservation treatment, to last some thirty years, using PEG 1000 up to 60 per cent in water solution. This plan was re-evaluated by Per Hoffmann, when he took his office at the German Maritime Museum in 1979 and after carrying out some tests from 1979 to 1984 (Hoffmann 2003, 81 and 84). The conservation started with PEG 1500 up to 12 per cent and switched in 1984 to the so-called "two-step" method, developed by Hoffmann, using two different molecular weights: PEG 200 up to 40 per cent (Hoffmann 2003, 86) and PEG 3000 up to 70 per cent (Hoffmann 2003, 87), both in water solution.

The conservation ended, in accordance with Hoffmann's plan, in December 1999. After some months of work, the ship was presented to the public on 17 May 2000 (fig. 7.1). The conservation was completed, but soon new issues surfaced: the ship "had been floating nearly weightlessly between 1981 and 1999 and had regained her weight of ca. 40 tonnes . . . and began to change its shape" (Hoffmann 2011, 151).

From 2002 to 2005 an international experts group worked under the supervision of Hoffmann on a new support system. The decision was taken to correct the deformed hull and go back to the drawing by the shipwright who reconstructed the ship in the 1970s (Hoffmann 2011, 153). To achieve this, metal structures were built in 2006 and the ship was put back in position in 2007.

In 2008–9 a laser scan was carried out by the company involved in the new support system, to make a mathematical model needed to manufacture a new girdle. After a short break, the project continued in 2013 with a new team. New solutions for the presentation of the ship were considered. An evaluation of the situation and the data collected highlighted the lack of information about the state of the object and the deformation processes, thus hindering the conception of a new support system for the ship.

Monitoring the Bremen Cog

Since the beginning of the project, the ship's shape, considered as a construction, was under the responsibility of the shipwright Werner Lahn (until 1987) and the engineer Wolf-Dieter Hoheisel (until 1999). The timbers were individually documented during the reconstruction phase, using a stereoscopic camera. In 1982 a photogrammetric campaign was carried out by Hannover University, focusing on the vertical lines in order to establish profiles using a metric camera. A new acquisition, requested by the museum's scientific committee, was carried out in 2003. Over one hundred digital photographs were taken and compared with the profiles from 1982. At that point "a distortion in the range of ±10 to 25 cm" was attested (Wiggenhagen et al. 2004, 54).

In 2009, a laser scanning acquisition of the inner part was conducted, in order to plan for a new metal support. Although a couple of three-dimensional records of the Bremen Cog were created, these constituted isolated initiatives, aiming to address specific, temporal tasks. No permanent, long-term deformation monitoring system was implemented.

The main challenge, in order to preserve the ship for future generations, is to understand it from within its core. In 2014 the design of a long-term deformation monitoring system, measuring the Bremen Cog at least two times a year, was considered the most sensible approach. A new support system for the ship conceived without tangible information about the deformation would not be logical.

Objectives of the Case Study

The case study, Bremen Cog—when Science meets the public, had two main aims. First, the ongoing monitoring of the ship's deformation and, second, the development of a means of interaction with museum visitors. In 2012, the German Federal Ministry of Education and Research published a concept paper for the eight national research museums, in which their role was defined as "a presentation platform for research and a bridge to education" (BMBF 2012, 2).[2] By acquiring three-dimensional data, rather than using the traditional methods, more goals would be achieved (Howard 2007, 5): research, informing the public about ongoing work and explaining further details about the object.

Three different 3D methods were to be tested exhaustively. The comparison would focus on such technical aspects as accuracy, acquisition duration, post-processing duration, as well as the choice of software, cost of instruments, the operator's expertise necessary to conduct an acquisition, data formats, and data archiving. The fusion would combine different data sets to optimize the 3D model and benefit from the advantages of each method. A 3D animation would be produced to be presented to the visitors.

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2 Citation translated from German by A. Colson.

User Needs

In the field of conservation-restoration, different techniques derived from chemistry, physics, and biology were developed over the time, called Conservation Science, in order to enhance knowledge about works of art. Some documentation techniques, such as digital photography, available at first only to prosperous institutions, became common practice. Nowadays almost every practitioner at a conservation laboratory has a digital camera. Unfortunately, not all cultural heritage objects receive equal attention. Some remain neglected and undocumented.

Monitoring and recording the condition of objects remains the central task of the conservator. First, it is essential to assess the current state of the object to identify a possible need for an intervention. Second, to keep a record of the conservation treatment of the object for future reference (E.C.C.O Professional Guidelines II, Code of Ethics, Article 10).

In this context, accuracy has to be defined by the conservator depending on the object's size and also the degradation to be documented. In the case of the Bremen Cog, it was decided to work at a level between 1.0 to 0.5 cm at first. After gaining a better overview of the deformation a re-evaluation would be made to see if more precision, around 1 mm if technically possible, would be needed.

As the conservator is required to document his or her work, the question of data sustainability arose. Would the data produced be accessible in ten, twenty and in a hundred years? Here lies the worry of working with digital instruments and tools, and maybe the reason why some professionals are still reluctant to use 3D technologies on a regular basis. The industry and engineering world charm the end-user with attractive case studies, promising very interesting results. But sometimes, reality appears to be more complex. End-users rarely engage directly with the technical field, unless they have some previous experience or an opportunity to address their questions in a specific research context.

Exploring different methods, or using different techniques to achieve a given objective, requires assessment of the costs involved. Following the project from start to finish and participating actively in the decisions is the only way for the end-user to gain a clear idea of the financial resources necessary.

The complexity of the hardware and software discourages the end-user from participation in the project. Working closely with the engineers and technicians plays an important role. More problems could be solved if conservators would be prepared to engage more with other fields, including with engineers from the information technology domain. In our case, if the deformation and climate data could be compared, patterns and similarities could be established and offer a factual basis for our theoretical assumptions.

Digitization methods

Location of the cog

The Bremen Cog is exhibited indoors, oriented towards the north, which means that starboard faces east. The ship is accessible on three levels. A large east window allows the visitors to look at the ship from outside, but constitutes a significant issue in preventive conservation, increasing the values of light on the object. Four pillars around the ship are made of concrete cubes, 60 cm in diameter. The temporary metal support is still in place and enables access to certain parts of the ship. On the backboard side, an elevator has been installed.

Common Coordinate System

Comparing three different methods requires a common coordinate system. The present recording project started in October 2014 with a coordinate system used for the photogrammetric acquisition conducted by Julien Guery. At that stage, eight reference points were installed around the ship, but none directly on it, exclusively on the ground floor. Together with colleagues from the Institute for Spatial Information and Surveying Technology, i3mainz, of the University of Applied Sciences in Mainz, the type of reference point was chosen and agreed upon. Black and white targets were printed on standard A4 paper (fig. 7.2).

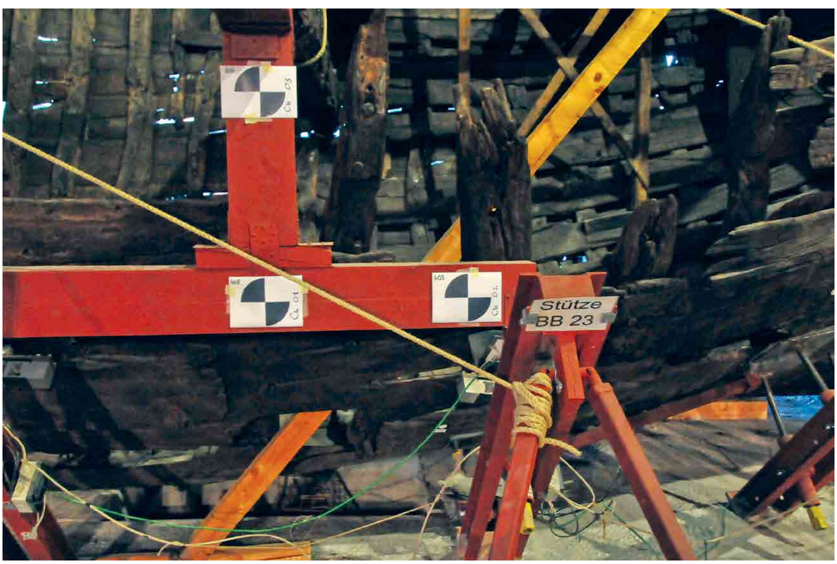

Figure 7.2. Bremen Cog, east side. Target on a concrete pillar. Photo © German Maritime Museum.

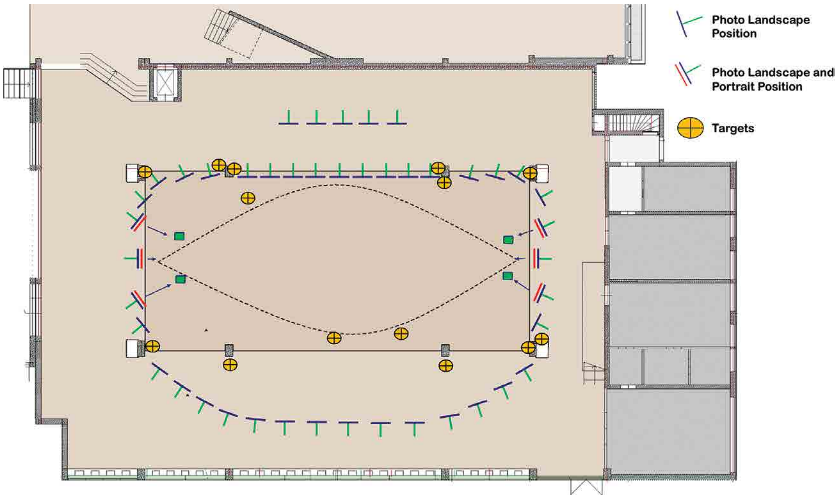

Figure 7.3. Bremen Cog floor plan, common coordinate system on the ground floor. © Amandine Colson.

The positions of the targets were selected in accordance with the 3D recording scanning positions. At least three targets had to be recorded from a single scanning position. Furthermore, since several recordings are needed to document the whole cog, the individual shots had to be aligned. The alignment of the required standard requires at least three identical targets for all 3D data sets. All targets were measured through tachymetric surveying in order to have a global reference system available for all future recording campaigns. Altogether, six more positions were added on the ground floor—making fourteen points (fig. 7.3), plus seventeen on the first floor, and five on the second floor.

When Massimiliano Ditta prepared the total station acquisition, in April 2015, the instrument required more reference points around the ship, and between the ship and the instrument, for the resection/repositioning. Nineteen reference points were therefore added, making forty-seven in total (Ditta 2015, 11). These points were used during the acquisition, and also for merging the different data sets.

To have one system that could serve all the requirements and was technically suitable proved to be a challenge. Although everyone knew that this was a testing phase, from the aesthetic point of view, it was difficult to justify almost fifty reference points.

Paper targets can only be a temporary solution. During the renovation of the room, twenty points were selected and had their centres drilled with stainless steel survey marker nails. The accuracy of this procedure has its limits, but the position of some points was maintained.

Table 7.1. Bremen Cog: Comparison of all photogrammetric data acquisition campaigns. © Amandine Colson.

Date	October 2014	October 2014	March 2015	April 2016
Operator	Julien Guery	Julien Guery	Julien Guery	Massimiliano Ditta
Duration of acquisition (hours)	2	2	1.5	1.5
Duration of post-processing (hours)	3*	2*	4*	12
Number of pictures	197	115	235	675
Pictures ground floor	72	39	80	252
Pictures first floor	74	33	75	207
Pictures second floor	51	43	80	216
Daylight (yes/no)	yes	yes	no	yes
Camera	Nikon D300	Canon IXUS - NIR	Nikon D300	Nikon D300
Software	Agisoft PhotoScan	Agisoft PhotoScan	Agisoft PhotoScan	Agisoft PhotoScan

* this post-processing includes aerotriangulation and 3D point cloud generation but no Digital Surface Model (DSM) or orthophotograph generation

The Institute of Photogrammetry and Geoinformation in Oldenburg, Germany, partners of the museum since March 2016, plans to work on technical questions such as the coordinate system and the reference points. A new coordinate system is to be implemented in 2017.

Photogrammetry

Three photogrammetric acquisition campaigns were carried out between October 2014 and September 2016. Those in October 2014 and March 2015 were undertaken by Julien Guery and the campaign in April 2016 was undertaken by Massimiliano Ditta (table 7.1).

The first acquisition campaign took place during Guery's Short Term Scientific Mission in October 2014. A three-week Mission was supported by the COSCH

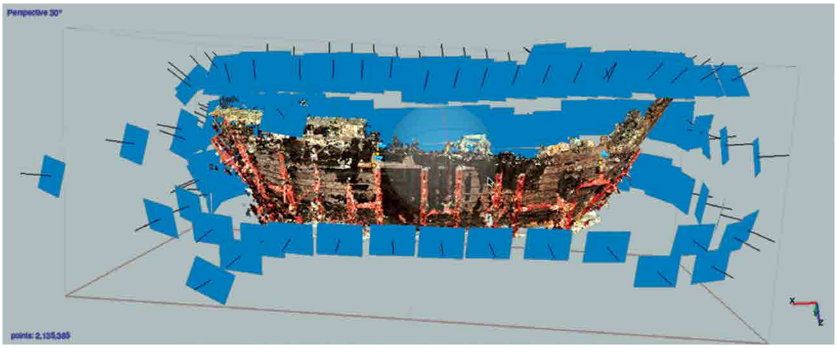

Figure 7.4. 3D photogrammetric model. © Julien Guery, 2015.

Action. Guery focused on local conditions, such as the daylight and the object material, a dark conserved wood (fig. 7.4).

After a couple of tests, it appeared that the best time would be late evening, when the sun goes down in the west or even later in complete nightlight. Other tests, using a modified camera to take pictures in the near-infrared range were promising. After solving these primary issues, the focus was on the acquisition itself.

Laser Scanning at i3mainz

In November 2014, the cog was recorded by Carina Justus and Stefan Mehlig from i3mainz using a Leica ScanStation P20. Twenty-nine scanning positions were needed to acquire a 3D data set representing almost the entire cog. The high number of scanning positions was needed due to:

1. the very complex shape of the cog: the inner and outer part both have many occluding areas;
2. as the inner part of the cog could not be entered due to its fragile conservation condition, the scanner had to be positioned outside the cog, on the ground level, to capture the outer part, and on the first and second levels of the exhibition room mainly to capture the inner part; and
3. the large size of the cog and the limited space around it (the field of view was small). Including the tachymetric surveying and laser scanning three days were needed.

The processing of captured data sets (registration, alignment, outlier removal, etc.) in all twenty-nine scanning positions was based on the local coordinate system and lasted ten days. The resolution of each point cloud was 6.3 mm @ 10 m; accuracy: 3 mm @ 5 m. A Leica ScanStation P20 (2013) was used. A tachymetric surveying with an accuracy of ca. 3 mm (adjusted) was applied to generate the local reference system. The aligned point cloud had ca. 30 million points (areas of no interest, such as the floor and roof, were deleted) with a resolution / point spacing of minimum 5 mm. The processed data were provided in PLY and OBJ formats which can be visualized and analysed with the open source software MeshLab. Due to the point spacing of minimum 5 mm a comparison of this data set with a qualitatively similar data set recorded in the future would provide information of geometric deformation of greater-than-or-equal-to 5 mm.

Total Station Theodolite

The total station is an electronic distance measurement device (EDM) used on building sites and archaeological excavations. A laser is pointed at a target and the position is recorded three-dimensionally. Thanks to a grant obtained through COSCH for a Short Term Scientific Mission, Massimiliano Ditta, an archaeologist and expert in 3D recording, worked for three weeks on the protocol and acquisition, using the Leica TS06 owned by the museum.

Usually in context of a monitoring, reflective targets are used for each point. Recordings can be made without targets, but the reproducibility of the recording cannot be assured. Installing targets would have meant drilling into the original wood, and was at that stage considered ethically unacceptable. If a long-term method is chosen, this question will be re-evaluated. The stickers used in earlier 3D scans were reused on the outside of the hull. For the inside, so-called feature points were defined by Ditta and catalogued.

The accuracy of the technique was ±2 mm cu., meaning an acquired data set can be compared with another one giving precise results. Usually, the data recorded with the total station are only seen during post-processing. It was possible to control the data acquisition through Rhinoceros software in real-time.

Presentation

As planned, the 3D models were used in another context, to promote the ship and the work of the Institute of Photogrammetry and Geoinformation in Oldenburg within the museum, and also externally. The historians and archaeologists are relying on animation (a mov format) to present their research into the cog at conferences. The present case study is a pilot project that aims to connect research and presentation.

In autumn 2016, a digital exhibition was organized by the eight museums of the Leibniz-Association, to celebrate the 300th anniversary of Gottfried Wilhelm Leibniz's death. It made use of the 3D data acquired during the case study. The animation was shown on a digital screen, installed on a large table, located outside

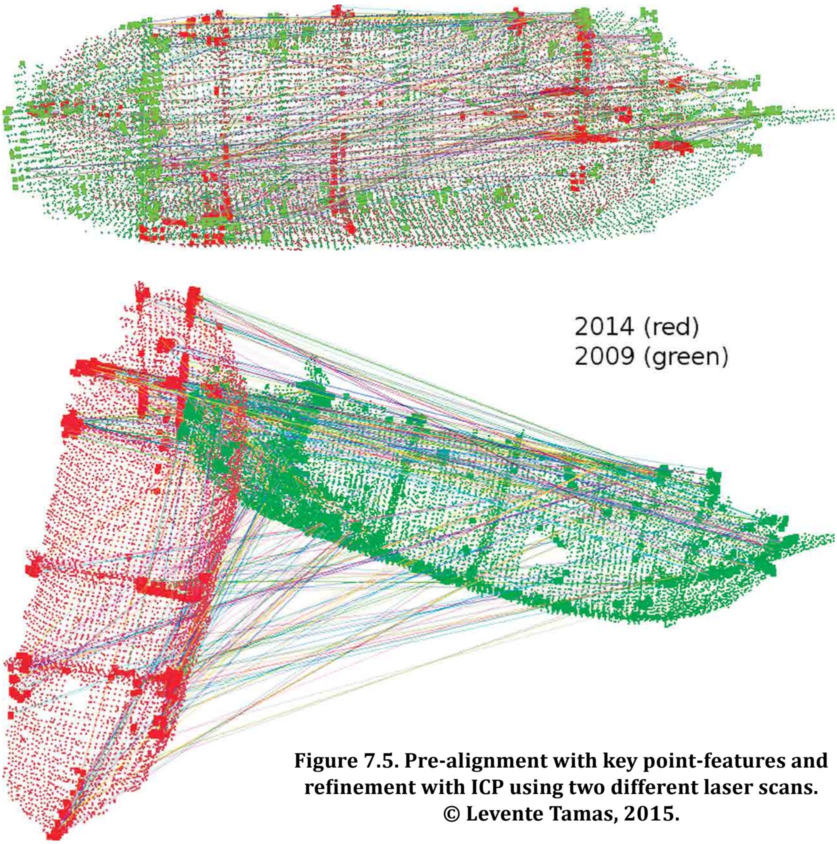

Figure 7.5. Pre-alignment with key point-features and refinement with ICP using two different laser scans. © Levente Tamas, 2015.

the conference hall of the German Maritime Museum. Historical and archaeological facts were added to complete the presentation. Visitors were given a chance to see the virtual ship, while the actual ship was covered during the ongoing renovation. In March 2017, the new exhibition surrounding the Bremen Cog opened. The digital models are used to present the ongoing research on the deformation monitoring.

Quality Evaluation

Each method uses specific software and tools. Software viewers do exist to visualize the 3D data, but a comprehensive custom evaluation was only possible during the Short Term Scientific Mission of Levente Tamas, in September 2015. The data were evaluated and compared over a week.

Beside the visualization of different 3D data, the main purpose of this investigation was to compare the scans taken at different times and with different

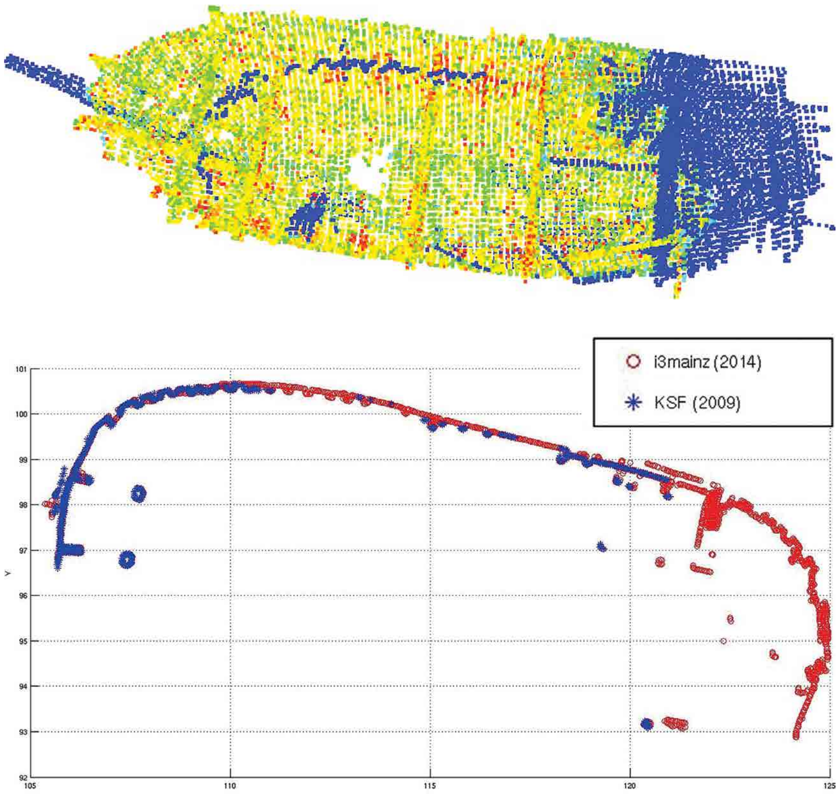

Figure 7.6. The entire body and the cross-section comparison of two different laser scanned measurements. © Levente Tamas, 2009 and 2014.

devices. The data collected prior to this case study were included, including a 3D scan completed by a private company in 2009.

Comparing heterogeneous data is not a trivial task. Adding a data set without geo-referencing makes it even more complicated. On the other hand, it was decided that it was relevant to test the comparison between similar acquisitions and continue with different ones. Each comparison method needs to be prepared for the next step. In the main literature for 3D data comparison purposes there are several methods for rigid body transformation estimation. From these we opted for the key point-feature-based pre-alignment and with Iterative Closest Point (ICP) refinement as shown in figure 7.5, where a scan from 2009 is shown in red and a scan from 2014 in green. This works well for the data of the same modality, and without non-linear distortion. However, for comparison of data of different modality (i.e., LIDAR vs. structured light) advanced non-linear deformation analysis has to be used.

For non-technical scholars an estimation of the entire 3D object, as well as the cross-section analysis, are both useful outputs of the comparison. Examples are shown in figure 7.6 where the entire ship is compared with local plane approximations, as well as a cross-section along the main axis of the object (green indicates small changes; red, bigger ones; and blue, no data).

Both visualizations have their advantages: the object level deformations are easily detected on the whole object visualization; however, for systematic analysis the cross-section can be more useful.

Handling Data and Metadata

In the course of this case study the data were stored in a shared cloud kindly provided by i3mainz. Each partner had easy access. At the end of the case study, all data produced will be stored at the German Maritime Museum. Metadata were not considered by the case study.

The data may be reused for further investigation by a Ph.D. project that started at the museum in March 2016.

Critical Discussion and Evaluation of Research

Different challenges arose during this project. The technical questions that had to be addressed included the pre-processing of data (e.g., conversion, including filtering), geo-referencing, registration of heterogeneous data, and comparison for deformation analysis. Articulating these questions was the first step towards finding solutions. The benefits of the chosen approach can inform other similar scenarios in the cultural heritage domain.

One of the technical challenges concerns the large size of the object whose view is obscured by surrounding objects, making the data acquisition difficult. The density and accuracy of the data, required to answer the initial question concerning deformation, were both important aspects of the volumetric data capture. The need to use the available older measurements and geo-reference them retrospectively was another aspect. A global overview and comparison of the different techniques may help other end-users to choose a method when working on similar projects.

For this purpose, a subjective comparison was made, allocating points to each technique. After different trials, the results could not provide complete consensus among the team and the comparison was abandoned. Moreover, the diagram showed that no technique offers a perfect answer and that either the methodology used during each acquisition campaign has to be questioned or it is simply impossible to compare different kinds of data sets produced through different techniques.

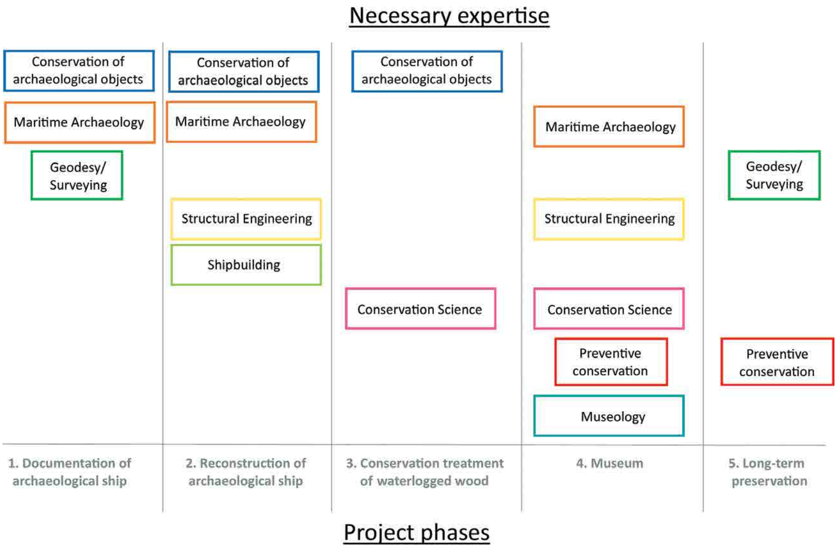

Figure 7.7. Expertise model chart. © Amandine Colson.

Last but not least, this project highlighted the considerable challenges to do with the different expertise involved. Interdisciplinary work is, without a doubt, the only way to solve such complex issues as deformation monitoring of an archaeological ship. Nonetheless the variety of backgrounds can lead to misunderstandings. Vocabulary misunderstandings were often mentioned as a central problem during the COSCH Action. This experience showed that the ways humanities and engineering researchers approach a problem vary profoundly. Cultural differences, connected not to nationality, but to the field of work, represented both an asset for the project and a challenge at the same time. Beside the intellectual challenge of understanding each other, planning work within the restricted timeframe and limited human resources was also an issue.

The contribution of interdisciplinary work was significant throughout the Bremen Cog project: from day one of fieldwork in the river Weser, to the reconstruction of the ship and the conservation treatment. Based on communication with colleagues involved in similar projects, a chart (fig. 7.7) has been elaborated to give an overview of the different fields involved in the project phases. This chart simplifies the fields of expertise required to answer the questions concerning the conservation and the presentation of an archaeological ship. It may serve as a reminder that such a complex project cannot be conducted singlehandedly, but is a result of decades of work involving various fields. The involvement of some fields is necessary during many phases, while others are only required once or intermittently. The chart presents the expertise involved and its impact on the dynamics of the project.

Conclusion and Future Research

This research continues as part of a Ph.D. project under the auspices of the German Maritime Museum, jointly supervised by Christoph Krekel of the State Arts Academy in Stuttgart and Thomas Luhmann of the Institute of Photogrammetry and Geo-information of the University of Applied Science in Oldenburg.

The approach chosen for this case study could be applied not only to other large-scale cultural heritage objects, such as wooden or metal ships, but also to larger sculptures and industrial objects exhibited indoors.

Photogrammetry will be tested further as a promising low-cost method. The partnership with the Institute of Photogrammetry and Geo-Information in Oldenburg is expected to help with the technical problems. A new coordinate system will be studied and a new acquisition protocol established in 2017.

Deformation monitoring of conserved ships appears to be an issue for other museums in Europe and so the creation of a specialist European working group is being currently discussed with colleagues in France, Norway, Great Britain, and Sweden. The first meeting is scheduled to take place in Bremerhaven in 2017. The problems raised during this case study will be addressed in other conservation/restoration networks or working groups and also amongst engineers. Possible solutions by other specialists should be investigated.

In order to build refined object models, based on non-linear shape registration methods, further investigations are necessary of the data treatment (including the SfM measurements) and advanced filtering of the heterogeneous data. Other interesting research includes the investigations related to the refitting of deformable object parts in an ensemble, that is, the separated planks in the deformed ship body, which is also a non-linear registration problem.

Basic education concerning digital technologies applied to the humanities should be discussed as part of any Bachelor's or Master's programmes. Limited training opportunities are available to graduate professionals, therefore the real experience and knowledge are gained through projects.

Chapter 8

A STUDY OF SPECTRAL IMAGING ACQUISITION AND PROCESSING FOR CULTURAL HERITAGE

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ABSTRACT

Imaging spectroscopy, specifically multispectral (MSI) and hyperspectral (HSI) techniques, has been advanced as an effective non-contact analytical tool for cultural heritage (CH). The combination of digital imaging and spectroscopy results in the ability to map the spatial distribution of materials over an object, extract reflectance spectra for the identification of materials, enhance and reveal underdrawings, identify past conservation treatments, and measure colour. Development and increased application of these techniques to documentation of CH calls for the definition of best practices, to allow institutions to have reproducible and comparable data.

Focusing on spectral object documentation, the Working Group 1 (WG1) of the COST-Action TD 1201, Colour and Space in Cultural Heritage, had the task of identifying, characterising and testing spectral imaging techniques and devices in the 400-2500 nm range. To assess the various spectral imaging systems, WG1 performed a Round Robin Test (RRT). Five objects were recorded by nineteen institutions with various MSI and HSI systems and setups. This coordinated research effort aimed to gain a better understanding of the instrumentation, the elements of data acquisition, and the effects of the instruments and methodology on the accuracy and reliability of the data.

Summarising and visualising the received RRT data illustrated the challenges and complexity of the assessment and comparison of the different datasets. Understanding the variation in the resulting datasets helped to inform best practices for CH. The experience was a means of working towards optimised methodologies to lead to the application of non-contact, high-resolution techniques in the state-of-the-art documentation of CH.

Keywords: Imaging spectroscopy, polychrome surfaces, reflectance, spectral image quality, image colour accuracy, cultural heritage imaging, calibration workflow, multispectral, hyperspectral, COSCH

Introduction

Imaging spectroscopy (IS) techniques, specifically multispectral imaging (MSI) and hyperspectral imaging (HSI), have presented promising advances in the field of non-contact analytical tools for cultural heritage (Fischer and Kakoulli 2006; Cucci et al. 2016). The combination of digital imaging with spectroscopy has expanded point-based, or one-dimensional (1D) spectroscopic techniques. IS provides the ability to distinguish and map the spatial distribution of materials over an entire object, extract reflectance spectra for the identification of materials, calculate colour, enhance and reveal underdrawings, detect changes in composition, and identify damage and past conservation treatments. The informative potential of applications and measurements is determined by the characteristics of the acquisition instrumentation. The increased application of IS techniques for the study and documentation of cultural heritage has resulted in the development of a range of spectral imaging systems. They are based, for example, on cameras with filtering systems or imaging devices with dispersive elements (MacDonald et al. 2013; Lapray et al. 2014). While the latter can offer better performance in terms of spectral resolution, they require sophisticated software and operator skills for the handling, processing, and interpretation of the large data sets acquired. Along with the variety of systems, procedures such as calibration, if not handled correctly, can make the comparison between the acquired data from different instruments impossible, as well as compromise the reliability of the data set. Related challenges include the lack of quality metadata collected in a standard way, the insufficiency of a shared common vocabulary, and the heterogeneity of file formats and software.

These challenges were acknowledged and addressed by Working Group 1 (WG1) of Colour and Space in Cultural Heritage (COSCH), which focused on spectral object documentation with the task of identifying, characterizing, and testing spectral imaging techniques and devices in the visible (Vis, 380–750 nm), near infrared (NIR, 750–1000 nm), and short wave infrared (SWIR, 1000–2500 nm) ranges. To assess the variety of systems and to work towards standardized methodologies and best practices for imaging cultural heritage objects through spectroscopic acquisition, WG1 carried out a Round Robin Test (RRT). Five objects were recorded by nineteen institutions (including museums, research organizations, universities, and IS equipment manufacturers) with various MSI and HSI systems and setups. The RRT was a coordinated effort to gain a better understanding of the instrumentation, the processes of data acquisition, and the effects of the devices and methodology on the reliability of the data. The challenges and issues that arose from bringing different data sets together and understanding the variability seen within them will help to improve protocols for the acquisition, handling, processing, and sharing of spectral data sets. The goal was the practical application of non-invasive imaging techniques in the documentation of cultural heritage.

This chapter reports some of the most significant results and experiences of the working group. The aim is the standardization of methods and the promotion of best practices to allow cultural heritage professionals to achieve accurate, reproducible and comparable data.

Earlier Research

Previous efforts have attempted to address colorimetric and spectroscopic imaging methodologies applied to the field of art conservation and documentation. There still exists a significant gap, however, in standardizing the application of spectral imaging techniques in academic, research and conservation laboratories. Several projects have contributed to the development of spectral imaging technology for the cultural heritage sector and have succeeded in designing high-performance hardware and software solutions for accurate image acquisition and processing. These started in the early 1990s with the VASARI project at the National Gallery, London, which achieved accurate high-resolution colorimetric images of paintings using a filter-based, multispectral scanning system in the visible region (Saunders and Cupitt 1993; Martinez et al. 2002). The CRISATEL project later extended the work into the NIR and applied basic spectroscopy techniques to the results (Ribés et al. 2005). Advances in technology made HSI possible in the 2000s. The use of pushbroom imaging spectroscopy was pioneered by IFAC-CNR in Florence (Casini et al. 2005) and by the National Gallery of Art in Washington (Delaney et al. 2010).

Although spectral imaging has been widely accepted by the cultural heritage community (Martin et al. 1999; Kerekes and Hsu 2004; Ribés et al. 2005; MacDonald et al. 2013), there remains a need to define guidelines for accurate image capture and a standardized workflow for processing raw data. Spectral image quality is influenced by a number of factors (Shrestha et al. 2014) and understanding their role and how different devices are used in the digital documentation workflow can help to define efficient procedures for acquisition and processing. This has been addressed through the COSCH RRT exercise, as presented in the following sections.

COSCH Round Robin Test: Description of Work

The RRT involved nineteen institutions acquiring MSI and/or HSI data from selected targets. These institutions included museums, research laboratories, universities, and hyperspectral equipment manufacturers. Five targets were used for the RRT (fig. 8.1): an X-Rite ColorChecker chart, together with its associated white card, a Russian icon, a wavelength standard, and a replica panel painting.

Round Robin Test

The first RRT object was the traditional standard X-Rite ColorChecker (280 mm × 216 mm) with twenty-four coloured square patches, each measuring 40 mm × 40 mm arranged in a four-by-six array. Although the ColorChecker does not fully represent the range of artists' materials or colour range, it is, nevertheless, a widely used colour reference target within the cultural heritage field and was employed to assess and compare the colour rendering characteristics of the various imaging devices.

The second object was the X-Rite white target, actually light grey in colour, which has the same dimensions as the ColorChecker and is coated uniformly with a paint that has a completely flat spectrum, that is, the same reflectance factor at all wavelengths. This was used to correct for non-uniformity of illumination, and also vignetting by lenses in camera-based systems.

The third object was a nineteenth-century, mass-produced Russian icon (265 mm × 220 mm), printed by polychrome lithography, using eight different inks, onto a tinned steel plate and nailed onto a wooden panel. It has a glossy surface over the coloured areas and a high specular reflectance from the golden metallic surface. The icon was used to investigate the spatial imaging characteristics of IS devices as well as their behaviour with highly reflective surfaces.

The fourth object was a SphereOptics Zenith Polymer Wavelength Standard (90 mm diameter × 15 mm thickness). Wavelength standards are reflectance targets designed for precise wavelength calibration of spectrophotometers, reflectometers, and other spectral instruments. This one is chemically inert, with a diffuse lambertian reflectance, composed of polytetrafluoroethylene (PTFE) doped with the oxides of the rare earth elements Holmium, Erbium, and Dysprosium. This combination gives the object a stable spectrum of characteristic, well-defined, and narrow features over the ultraviolet (UV, 200–380 nm), Vis, NIR, and SWIR spectral ranges, making it particularly suitable for accurate spectral calibration. The wavelength standard is supplied with traceable, laboratory-certified reference reflectance measurements covering the 200–2500 nm range. It was used to assess and compare the spectral accuracy of the imaging devices.

The documentation and study of works of art, in particular paintings, was the objective of the spectral imaging carried out by the participating teams. The fifth target was therefore painted. It was made especially for the RRT, using the medieval Tuscan panel painting technique, based on egg-tempera paints, described by Cennino Cennini in his *Il Libro dell'Arte* believed to be written in the 1390s (Cennini 1954). The panel (290 mm × 220 mm) consists of a wooden support with a gypsum ground, a canvas layer, and a second gypsum ground layer. Five types of drawing materials—watercolour, charcoal, graphite, a lead and tin-based metal-

Figure 8.1.
(a) X-Rite ColorChecker with sampling areas for colorimetric and spectral analysis; (b) SphereOptics Zenith Polymer Wavelength Standard; (c) Russian icon with sampling areas for colorimetric and spectral analysis; (d) replica panel painting with sampling areas for colorimetric and spectral analysis.

Table 8.1. Specification of the imaging devices used in the RRT.

	System attribute		
	Operative range (nm)	No. bands	Spatial sampling (pix/mm)
MSI LCTF	400–720	33	4.2
MSI LCTF	400–720	33	6.8
HSI pushbroom	400–900 950–1650	400 332	9–11
HSI pushbroom	400–1000	160	16

point, and a lead-based metalpoint—were used to create lines and line patterns that were then covered with paints applied with two different thicknesses. Seven pigments—carmine, vermilion, burnt umber, malachite, azurite, lead white, and ivory black—were mixed in an egg tempera binder and applied to the panel. They were chosen to have distinctive spectra in the Vis, NIR and SWIR spectral ranges allowing useful spectral analysis to be carried out in any spectral region.

Methodologies

Imaging spectroscopy is normally classified as either multispectral (MSI) or hyperspectral (HSI) but the distinction between the two is rather blurred (Liang 2012). The number of bands, their width and continuity are the parameters by which the two techniques differ. MSI systems are designed to acquire images over a limited number of spectral bands, usually with a set of filters having bandwidths from tens to hundreds of nanometres. HSI systems acquire images in narrower and more numerous contiguous bands, typically 100 or more having bandwidths from 1 to 10 nm. The advantage of HSI systems is to provide almost continuous spectral measurement, and therefore they are more accurate than MSI in spectroscopic analysis and material identification (Cucci et al. 2016).

There are several methods of wavelength selection which determine the design of the illumination and the spatial and spectral scanning strategy. For MSI devices tunable light sources may be employed, such as LED-based or filter-based lighting systems, with a monochrome digital camera. Alternatively white light sources may be used with filtered cameras, in which a filter wheel or tunable spectral filters, such as Liquid Crystal Tunable Filters (LCTF) and Acousto-Optical Tunable Filters (AOTF), are placed in front of the sensor (Lapray et al. 2014).

Most of the available HSI systems are based on prism-grating-prism (PGP) line-spectrographs connected to high-sensitivity detectors and the data acquisition is made in pushbroom modality, in which a complete spectrum of each point

		Setup information		
Spectral sampling (nm)	No. bits	Complexity	Portability	Cost*
10	12	Medium	High	M
10	16	Medium	High	M
1.3 2.1	14	High	Low	E
3.5	14	High	None	E

* Cost: C = cheap (<€30,000); M = medium (€30,000–€50,000), H = high (€50,000–€80,000) and E = expensive (>€80,000).

Figure 8.2. Different spectral imaging devices used within RRT. Left MSI; right HSI.

along a line is formed on one column of the 2D detector array and the area of interest has to be scanned one line at a time. A different HSI technology uses snapshot imaging spectrometers, which collect the entire data set (or data cube) in a single integration period without scanning (Hagen et al. 2012). Although the acquisition of a large number of contiguous narrow bands allows an accurate spectral acquisition, these systems are usually more complex, which decreases their portability and increases their cost. Some configurations of the MSI and HSI systems used in the RRT (fig. 8.2) are summarized in table 8.1.

The two most important characteristics of MSI and HSI systems are their spatial and spectral resolutions, which are linked to their spatial and spectral sampling characteristics. The former is a measure of a system's ability to resolve the desired details in the surface of an object of interest. There are different definitions for the factors related to spatial resolution, including pixel resolution (the number of pixels per linear mm) and optical resolution (the ability of an imaging system to resolve closely-spaced points). Pixel resolution influences the spatial resolution of an image, but is not the only criterion used to evaluate the resolving capabilities of a system. A higher pixel count may increase the image size, but does not guarantee a high spatial resolution, which depends on both optical and electronic components including the lens, aperture, detector, and signal processing (Cucci et al. 2016; MacDonald 2010). The spectral resolution, on the other hand, defines how well the system can resolve the spectral features by sampling wavelength, and is important for material identification (Cucci et al. 2016). Materials can be identified based on their characteristic spectral features, both absorption and reflectance, which can be observed with spectroscopic techniques including IS. Some materials have very narrow spectral features that can only be resolved by systems with a high spectral resolution, whereas other materials have broader features that can be resolved by systems with a lower spectral resolution.

Comparison and Evaluation Procedures

Colorimetric and Spectral Analysis

For data comparison a set of areas was selected on the X-Rite ColorChecker and in the Russian icon (figs. 8.1a and 8.1c). At each of these locations spectral reflectance data from the IS systems were averaged and compared with values obtained from a spectro-colorimeter (Minolta CM-2600d) with a d/8° geometry (fig. 8.3). For non-uniform surfaces such as those of the icon, these measurements may express combinations of rather different spectra. It should also be noted that as the geometry of the spectro-colorimeter is different from that of the imaging systems direct comparison of the results must be made with caution. The CIE L*a*b* coordinates were calculated using the CIELAB 1976 colour space with D65

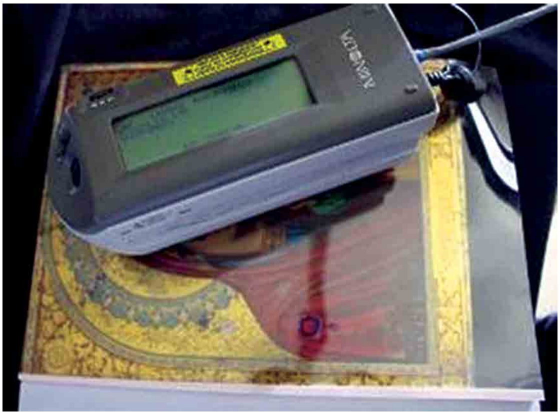

Figure 8.3. Minolta CM-2600d measuring reflectance spectra on selected areas of the Russian icon.

illuminant and 2° standard observer. The CIEDE2000 formula was used to calculate the colour (ΔE_{00}) and chroma differences ($\Delta C'$) to compare the acquired and processed data (CIE 2004).

To compare the reflectance spectra extracted from the data acquired by each device with those acquired with the Minolta, two measures were used: the Root-Mean-Square Error (RMSE) and the Goodness-of-Fit Coefficient (GFC) (Valero et al. 2007). RMSE represents the standard deviation of the differences between two spectra, and GFC represents the cosine of the vector angle formed by those spectra. The two measures of performance differ since GFC is not affected by scale factors. The value range is from 0 to 100%, with a GFC ≥ 99.5% corresponding to acceptable recovery and GFC ≥ 99.99% to an almost exact fit.

Spatial Resolution Assessment

Spatial resolution may be evaluated using diverse approaches (Holst 1998). Here three methods for assessing the spatial resolution are presented: visual comparison of resulting images, plotting of cross-sectional profiles, and calculation of the sampling density. The most straightforward way of assessing the spatial resolution of a system is to look at how well the resulting images resolve the details of the documented object. The second way is to plot the intensity profiles of a sequence of high-low reflective materials to determine the contrast between lines and spaces, such as line patterns on the replica panel painting (fig. 8.1d). For this object, for instance, as the resolution decreases, the ability to discriminate lines and spaces and the distance between peaks and valleys in the profile plots decreases. The third way is to calculate the sampling density, by dividing the number of pixels between two points by the corresponding physical distance, expressed as pixels/mm.

Spectral Alignment Accuracy

Spectral alignment accuracy can be obtained by using "spectrally well-known light sources" such as fluorescent lights, xenon or mercury lamps that exhibit distinct and stable spectral features (Polder et al. 2003). An alternative approach is through the use of reflective targets impregnated with rare earth oxides (such as holmium oxide, erbium oxide, and dysprosium oxide) that present discrete narrow and strong absorption bands (Burger 2006). In the RRT a SphereOptics Zenith Polymer Wavelength Standard was used (fig. 8.1b).

Results for Each Object

X-Rite ColorChecker

The ColorChecker was used to evaluate the colour and spectral accuracy of the different devices (fig. 8.1a). Colour differences and other colorimetric parameters calculated from the data acquired by four participating institutions are presented. Specifically, the discussion of those results is centred on: (i) the accuracy of colour and spectral reproduction of the ColorChecker; (ii) the problems related to non-homogeneity of the colour surface; and (iii) the definition of the most problematic areas (hues) for accurate colour and spectral recording.

Colour accuracy was verified by comparing the colorimetric values calculated from the MSI and HSI data with those obtained from direct measurement with the spectro-colorimeter. Figure 8.4a shows the average ΔE_{00} (black symbols) and $\Delta C'$ (red symbols). Colour difference values are in general low and in all cases below four units. As expected, systems with a larger number of spectral bands approximate better (fig. 8.4a devices 3–4) to the spectrophotometer measurements than those with a small number of bands (fig. 8.4a devices 1–2). Comparison of the RMSE and GFC (figs. 8.4b and 8.4c, respectively) suggests that when scale factor is eliminated the performances of both types of systems are very similar.

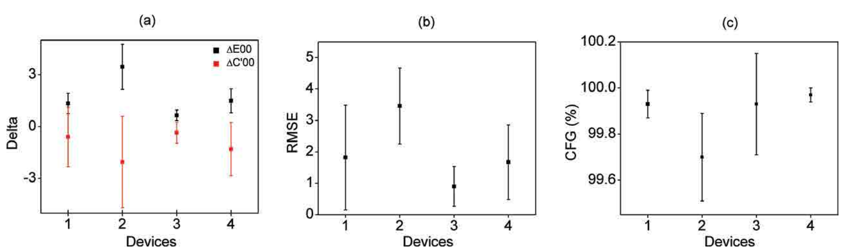

Figure 8.4. ColorChecker, comparison between the four imaging devices (MSI = 1, 2; HSI = 3, 4) and the spectro-colorimeter measurements: (a) ΔE_{00} and $\Delta C'$, (b) RMSE, and (c) GFC data.

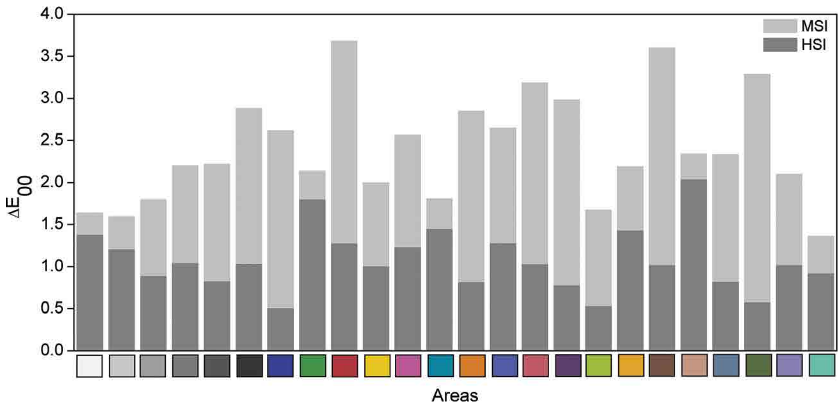

Figure 8.5. ΔE_{00} for the twenty-four coloured areas of the ColorChecker. Average results for MSI and HSI devices.

Regarding points (ii) and (iii), the colorimetric comparisons between one MSI and one HSI system against the spectro-colorimeter data across coloured samples expressed in ΔE_{00} were also evaluated (fig. 8.5). The threshold for colour discrimination for human vision is considered 0.3 for uniform samples (Martínez-García et al. 2013), and 3 for image reproduction (FADGI 2016). In figure 8.5, the averaged HSI results show a ΔE_{00} very close to the human limits for colour discrimination with the exception of the green (no. 8), red (no. 9), dark skin (no. 19), and foliage (no. 22) patches. The reference data were acquired with a different geometry from the MSI and HSI devices, which can impact the resulting measurements and comparison. Despite the differing geometries, the data acquired from the MSI and HSI devices are consistent with each other and the spectro-colorimeter.

Russian Icon

The Russian icon was selected to establish the imaging performance of systems (fig. 8.1c). It was also useful to study the ability of devices to cope with the specular reflectance from its glossy metallic surface.

The results for the Russian icon (fig. 8.6) show that the differences, at both spectral and colorimetric levels, between the values extracted from the IS data and those measured with the Minolta spectro-colorimeter were larger than those found with the ColorChecker (fig. 8.4). This is a consequence of the fact that the surface of the icon is not diffuse and, here, the measurement geometries of the different devices are critical. However, the differences calculated within this RRT for the Russian icon are still relatively small.

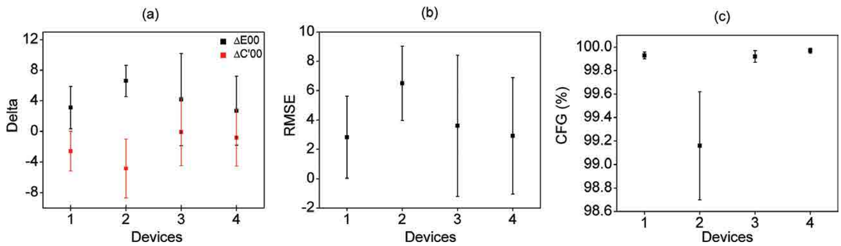

Figure 8.6. Russian icon, comparison between the four imaging devices (MSI = 1, 2; HSI = 3, 4) and the spectro-colorimeter measurements: (a) ΔE_{00} and ΔC', (b) RMSE, and (c) GFC data.

The capability to resolve the fine spatial details of the icon also provides an indication of the spatial resolution of each system. An example of such detail extracted from three of the systems is presented in figure 8.7.

The ability of the four IS devices considered here in extracting spectroscopic data from the icon is shown in figure 8.8. It is evident that there is a sufficiently good accordance among those imaging systems in the obtained spectral shape of the spectra. However, those reflectance spectra cannot be perfectly superimposed due to differences in their reflectance values across the recorded spectral range. The blue vest and the skin were probably obtained by mixing a white pigment with Prussian blue and a red dye, most likely an anthraquinone-based dye, respectively.

SphereOptics Zenith Polymer Wavelength Standard

As wavelength standards are designed for use with spectral equipment with high spectral resolution, the analysis in this section is limited to the available data from HSI equipment only. The measured reflectance spectra of the wavelength standard for each HSI system were determined by taking an average over several thousand pixels, thereby significantly reducing noise. The spectral responses of the different systems for the wavelength standard are shown in figures 8.9 and 8.10, together

Figure 8.7. Russian icon detail extracted from the different devices to show the spatial resolution quality from three IS systems.

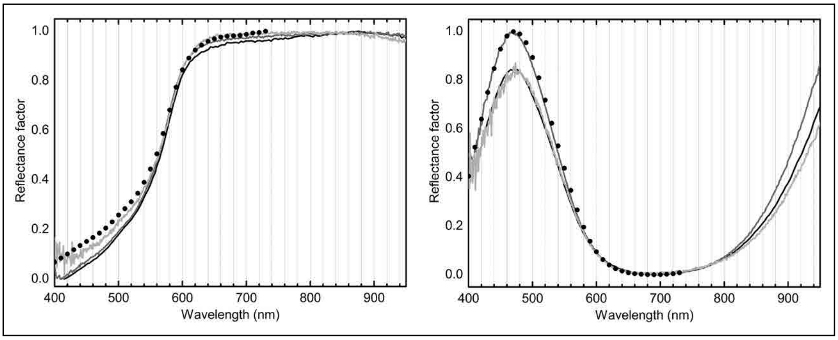

Figure 8.8. Reflectance spectra from two different coloured regions (skin and blue vest, respectively) of the Russian icon reconstructed from the MSI and HSI data sets.

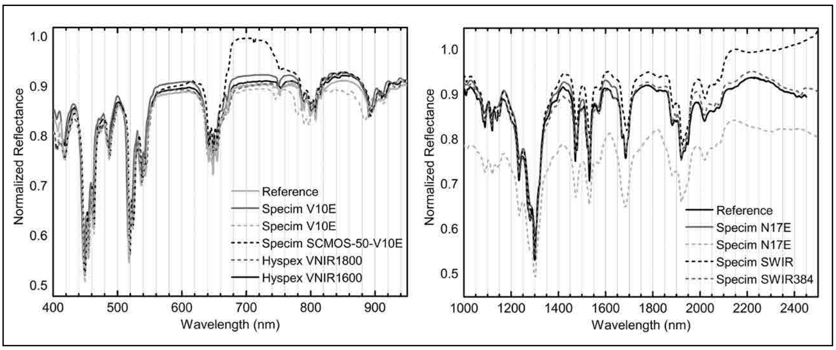

Figure 8.9. SphereOptics Zenith Polymer Wavelength Standard. Comparison of Vis-NIR (left) and SWIR (right) reflectance.

with the certified reference values for the standard supplied by the manufacturer. The Vis-NIR and SWIR wavelength regions are shown separately. Although the spectra are broadly similar, there is a clear variability in amplitude, spectral shape, and also spectral misalignments between the reference spectra and the calibrated data from the various HSI systems.

The reference standard contains sharp narrow absorption bands and troughs, which in several cases are beyond the spectral resolution even of the HSI systems. Each system has slightly different wavelength ranges, different numbers of bands with different central wavelengths, and different bandwidths at each wavelength. Therefore, in order to make meaningful quantitative comparisons, it was first necessary to resample each of the acquired data to a common sampling basis and to convolve the reference spectra at the central wavelength for each band with a Gaussian distribution with the camera's given full width half maximum (FWHM) in order to mimic the spectral and bandwidth characteristics of each HSI system.

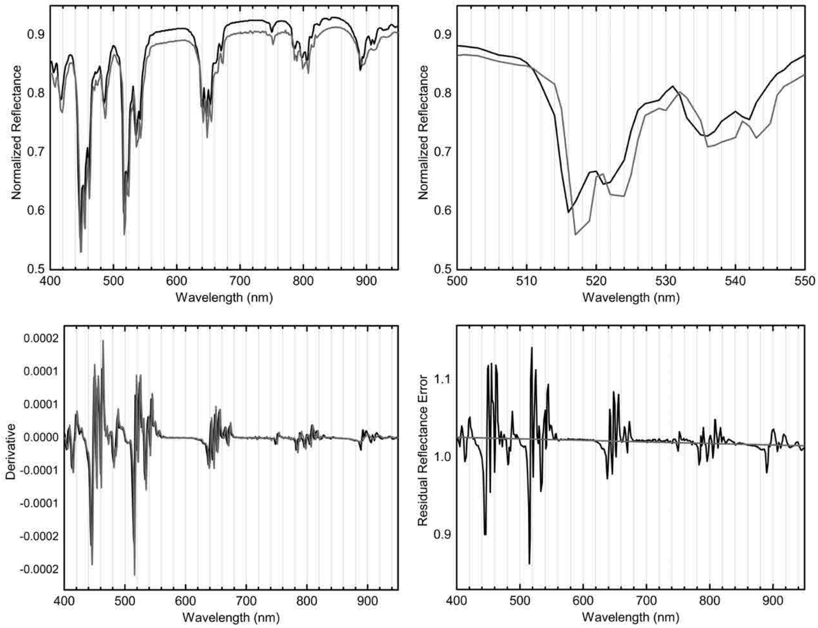

Figure 8.10. Comparison of the reflectance spectra of wavelength standard for one of the Vis-NIR hyperspectral systems (top left), a zoom of a narrow range of wavelengths showing spectral misalignment (top right), the derivative of the spectra (bottom left), and the residual error with its linear regression (bottom right). Reference = grey line; Vis-NIR hyperspectral system = black line.

The residual error was calculated for each system from these resampled reference spectra (fig. 8.10). Although there are large errors at the sharp bands and troughs, the average errors are relatively small, ranging from 0.005–0.01 in the Vis-NIR region, but much higher in the SWIR region.

The spectral misalignment that can be seen in figures 8.9 and 8.10 can be better visualized by comparing the first derivatives of the two spectra. The zero-crossings correspond to the position of the absorption bands and bottoms of the troughs of the reflectance spectra. The results from a single HSI system are shown in figure 8.10, where a small spectral misalignment can be clearly seen in the zoomed view. In order to quantify this, phase correlation was used to measure a global offset between the resampled reference signal and the measured spectra. The results in table 8.2 show that this spectral misalignment ranged from 0.0 nm to 2.6 nm in the Vis-NIR region and from 0.0 nm to 2.0 nm in the SWIR region for the two different HSI systems.

Table 8.2. Spectral misalignment errors of the different devices.

Vis-NIR		SWIR	
System	**Misalignment (nm)**	**System**	**Misalignment (nm)**
Hyspex VNIR1600	0.0	Specim N25E MCT	0.0
Hyspex VNIR1800	-0.1	Hyspex SWIR384 MCT	0.3
Specim V10E	1.0	Specim N25E MCT	0.8
Specim V10E	-1.3	Specim N25E InGaAs	2.0
Specim SCMOS-50-V10E	1.3	Specim N25E MCT	2.0
Specim V10E	2.6*		

* This system has very noticeable wavelength-dependent misalignment.

Replica Panel Painting

The replica panel painting was employed to assess the ability of HSI systems to identify and characterize pictorial materials, and their spatial resolution in the NIR-SWIR region to unveil and study underdrawings. Visual comparison of images acquired from the two HSI systems provided an indication of the spatial resolution of the resulting data. As an example, a detail extracted from one of the HSI data sets (fig. 8.11) shows how the three sets of watercolour lines with spacing from 2 mm down to 0.5 mm were resolved. The true sensitivity in the spatial resolution of IS devices can be visualized by plotting the intensity profiles of the line patterns on the panel painting. The reported plot of the profiles of the watercolour

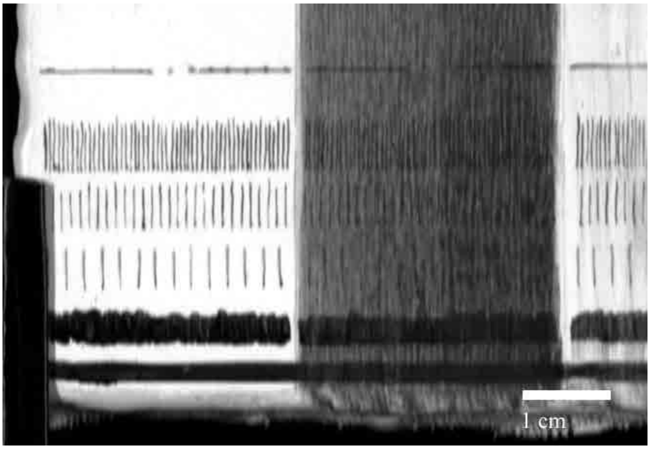

Figure 8.11. Detail of the replica panel painting extracted at approximately 1040 nm looking at the line patterns to assess the system's ability to resolve fine details.

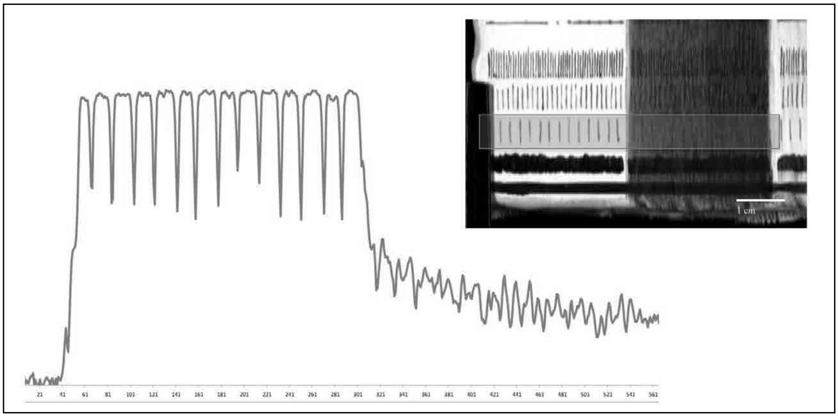

Figure 8.12. The vertical profile (left) from an HSI device data set looking at the exposed watercolour lines (right image) on the replica panel. The system is able to differentiate between the lines and spaces as seen with the well-defined peaks.

lines with 2 mm spacing shows a clear differentiation of the lines and spaces with greater distance in amplitudes between the peaks and valleys (fig. 8.12).

Concerning the NIR-SWIR region, even if it is possible to discriminate the areas presenting fine details, such as the lines with 1 mm pitch (fig. 8.13), the visualization of these underdrawings depends on the transparency of the paint layers. The ability to reconstruct images at different wavelengths from an HSI data set allows the user to penetrate deeper into the layers and obtain a higher degree of visualization. As an example, for the azurite layer, it was possible to observe the underdrawing clearly at ~1300 nm, whereas for the malachite layer, the lines were only legible at ~1600 nm. For both pigments, IS devices limited to a maximum wavelength of 1000 nm would not have been able to detect underdrawings behind such pigments.

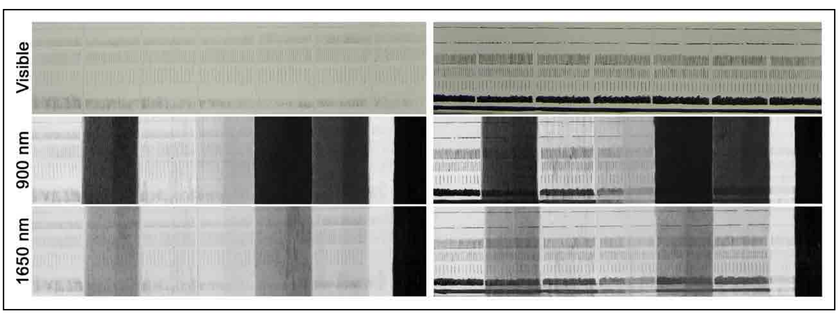

Figure 8.13. Images extracted from the hyperspectral data cube at two different wavelengths for the visualization of underdrawing details made with lead- and tin-based metalpoint (left) and watercolour (right) techniques.

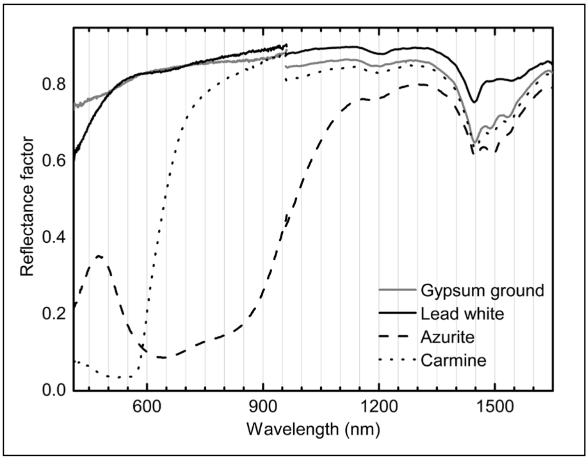

Figure 8.14. Reflectance spectra from the painted areas made with carmine lake (dotted line), azurite (dashed line), lead white (solid line), and gypsum preparation (grey line) of the replica panel painting.

Due to the high spatial and spectral sampling of some HSI devices, reflectance spectra from areas of 100 mm or less can be collected on fine polychrome objects. Vis-NIR-SWIR reflectance spectra extracted from the HSI data of the carmine-based red lake, azurite, lead white, and gypsum are reported in figure 8.14. In this spectral region gypsum can be identified by its three sub-bands in the 1447–1532 nm range; lead white can be identified by the presence of a spectral feature at 1450 nm; and azurite has its own distinctive absorption band at 1500 nm. Azurite also presents an intense characteristic absorption in the red-NIR region. Spectra of carmine red lake, on the other hand, in the case of paint layers that are less saturated, have a main absorption band in the Vis-NIR structured into two sub-bands at 530±5 nm and 567±3 nm. To identify those spectral bands precisely an IS device with high spectral resolution is usually required.

Discussion and Conclusions

The RRT was a coordinated research effort to explore the instrumentation, the differing protocols of image acquisition, and the effects of the instruments and methodology on the accuracy and reliability of the data. It has provided an important insight into the reliability and comparability of IS systems and methodologies in use within the cultural heritage field.

In this chapter, the results of the assessment of a subset of the data sets, consisting of representative MSI and HSI systems has been presented. The devices and procedures from the RRT provide broadly consistent results with average colour differences at or below accepted thresholds and largely accurate spectral reproduction. There was, nevertheless, considerable variability in the data.

Sources of this variability included the equipment itself (MSI vs HSI, manufacturer, specifications), the users (museums, universities, research laboratories), and the methods of data processing (procedures and workflow), which resulted in varying levels of quality in the final spectral data.

In addition, there were several sources of error that affected the resulting data and measurements. These included errors in spectral alignment, noise, and distortions including amplitude as well as spatial distortions. Such errors can have important consequences for the use of spectral data in applications such as materials classification or pigment mapping, degradation monitoring, and colorimetry.

The results have highlighted the need to work towards standardized methodologies and the need to define best practices. It is important for cultural heritage users to understand the calibration (spectral, radiometric, and spatial calibration) workflow as well as understand the true accuracy, precision, and limits of the systems. Improved acquisition protocols and workflows can dramatically improve the accuracy and reliability of the measurements and the resulting data. In addition, the RRT made clear the importance of regular calibration, validation, and testing of the system.

Finally, it is important to stress the interdisciplinary nature of IS methodologies. Their application in the field of cultural heritage requires a blend of interdisciplinary expertise and collaboration, with specialized skill sets and knowledge that contribute to the outcomes of the research project. This aspect is crucial to obtain satisfactory and reliable results.

Chapter 9

ONTOLOGY-BASED STRUCTURING OF SPECTRAL AND SPATIAL RECORDING STRATEGIES FOR CULTURAL HERITAGE ASSETS: BACKGROUND, STATE OF AFFAIRS, AND FUTURE PERSPECTIVES

ASHISH KARMACHARYA and STEFANIE WEFERS

ABSTRACT

The activities of COSCH community and the disciplines it represents were as diverse as they could possibly be in research into cultural heritage. To achieve common goals it was of utmost importance to have a common understanding of these diverse activities and disciplines. Work on the COSCH Knowledge Representation, or COSCH^{KR}, was undertaken to develop a common semantic base representing different disciplines and to facilitate communication within the Action. The COSCH^{KR} is an ontology-based inference model, guided by inference rules that provide a semantic bridge between various interdisciplinary activities involved in non-invasive technical documentation of material cultural heritage. The model is intended to support humanities experts by recommending optimal spatial and spectral techniques. The model may also be used by technology experts to compare their own solutions with the ones recommended through COSCH^{KR}, and to understand why they may differ.

In this chapter we present the methods adopted for designing the COSCH^{KR} and the steps in the development of the inference model. The difficulties in maintaining a common level of understanding within the diverse disciplines during the knowledge acquisition process are discussed. We present mechanisms and methods of information collection, its structuring, and aligning, to formulate different axioms and theorems within the model. The design and development of COSCH^{KR} was based on an iterative procedure where the gathered knowledge was first verified with the group of experts before it was processed. This verification mechanism was important for the reliability of the model, ensuring technical consistency. This chapter highlights the importance of these iterative mechanisms in the validation of knowledge gathered and then information populated inside the knowledge base.

Keywords: COSCH ontology, knowledge representation, cultural heritage recording, Semantic Web technologies, inference system

Introduction

Spectral or spatial recording of material cultural heritage (CH) is an interdisciplinary task involving scientists and experts from the humanities, information technologies, and engineering. A mutual understanding and agreement about the complexities of undertaking such recoding tasks is necessary in order to deliver appropriate spectral or spatial data of physical cultural heritage objects adapted to the needs of cultural heritage experts who rely on and work with those data. The COST Action TD1201: Colour and Space in Cultural Heritage (COSCH) (Boochs 2012; Boochs et al. 2013), brought together these experts to enhance mutual understanding among the disciplines in order to better record and preserve material cultural heritage. In addition to preparing guides to good practice for cultural heritage documentation through publications, the COSCH experts have structured the relevant knowledge into a machine-readable format. This logically structured machine-readable expert knowledge has been encoded in the COSCH Knowledge Representation ontology or $COSCH^{KR}$.

$COSCH^{KR}$ is intended to work as a catalyst simplifying interdisciplinary communication between technical and heritage experts in implementing the recording and processing of the data. By exploiting the encoded knowledge representation in $COSCH^{KR}$, cultural heritage experts will benefit from recommendations for suitable recording strategies. Apparently, as there is no all-in-one solution, these recommendations are based on the specific cultural heritage object and the required cultural heritage application. In addition, important factors that may influence the choice of the appropriate recording strategy, such as the lighting conditions, access issues, project-dependent limitations, etc., are also taken into account and are encoded inside the ontology. They will be inferred against other classes inside the ontology for recommending the optimal recording strategy. The $COSCH^{KR}$ platform, which is currently under development, will encapsulate the ontology and the inference mechanism through interactive user interfaces for providing the recommendation based on the inference results. The intention of the $COSCH^{KR}$ platform is to readily provide heritage experts with an overview of optimal spectral and spatial recording strategies according to their needs and not to educate them on the technicalities of spatial and spectral recording disciplines.

This chapter describes the motivation behind the development of the $COSCH^{KR}$ platform and advocates the significance of such a tool supporting smooth communication in interdisciplinary cultural heritage research projects. It also points out the complexity of handling interdisciplinary knowledge within a single ontology (cutting across disciplines with entirely different interpretations).

Earlier Research

Increasingly ontologies are evolving as major computational artefacts that provide logical representations of a particular domain of interest. They are generally used to represent knowledge providing a computational model of a particular domain of interest (Jakus et al. 2013). Ontologies allow sharing and reuse of knowledge and have become a popular research area in the Semantic Web because the sharing and reuse of knowledge within inter-communicable domains is the primary objective of the Semantic Web (Studer et al. 1998).

The most prominent ontology for cultural heritage disciplines is CIDOC-CRM (Boeuf et al. 2013), which was designed as a standard for stakeholders such as museums archiving cultural heritage objects. Though the terminologies used within CIDOC-CRM are of interest for the research in COSCH, and CIDOC-CRM is actually referenced inside $COSCH^{KR}$, the intention and application of $COSCH^{KR}$ differs considerably from CIDOC-CRM. Moreover, CIDOC-CRM does not provide a class structure for detailed information about the recording of cultural heritage objects. Therefore, it is not possible to make use of CIDOC-CRM. The CARARE 2.0 metadata schema (D'Andrea and Fernie 2013) prepared within the framework of the 3D ICONS project[1] provides compatibility with the structure of CIDOC-CRM. CARARE 2.0 is the second version of the CARARE schema[2] that was developed within the CARARE project, defined to support the harvesting and aggregating of metadata for Europeana. CARARE 2.0 is based on cultural heritage standards such as MIDAS (Lee et al. 2012), an XML-based harvesting schema LIDO (Coburn et al. 2010), and the EDM-Europeana Data Model (Charles 2013). It harvests meta-, para-, and provenance data of 2D and 3D data of cultural heritage objects into Europeana.[3] The schema extends the class including technical para- and metadata of recording strategies. However, it is meant to harvest the content into open knowledge hubs for linking data. It does not offer provision for making the choice of optimal para- and metadata from the existing content, when new cases arise. The development of the CARARE 2.0 metadata schema thus follows a pattern that is necessary for ontologies which manage and harvest content.

We concluded that to provide a tool which supports cultural heritage experts in finding the best suitable spatial or spectral recording strategy adapted to their application, it is necessary to develop a new common ontology. It is not possible to integrate existing domain ontologies since first, not all involved disciplines

1 http://3dicons-project.eu/index.php/eng.

2 http://pro.carare.eu/doku.php?id=support:metadata-schema.

3 http://pro.europeana.eu/.

have their own well accepted ontology (cultural heritage has CIDOC-CRM, but for spatial and spectral technology there is no widely accepted one) and second, ontologies are designed for different purposes and scopes (e.g., CIDOC-CRM is designed for providing standards for museums archiving physical cultural heritage objects (Boeuf et al. 2013) or OPPRA.owl is designed for twentieth-century paint conservation (Odat 2014)); thus harmonizing them via inference rules is a long and tedious task.

COSCH^{KR} is able to facilitate recommendation through rules that are encoded within the ontology. Therefore, one may argue that it is possible to build a Recommender System (RS) upon this ontology. A RS is a software tool and technique providing suggestions for items to be of use to a user (Ricci et al. 2011). However, RSs traditionally rely on stochastic methods, as in the case of machine learning, to infer the recommendation. This requires significant data for their interpretations. Although recently ontologies have started to be used in combination with the traditional methods (Middleton et al. 2009; Rodríguez-García et al. 2015), they are limited for the profile matching of the users in focus and do not partake actively in inferring recommendations.

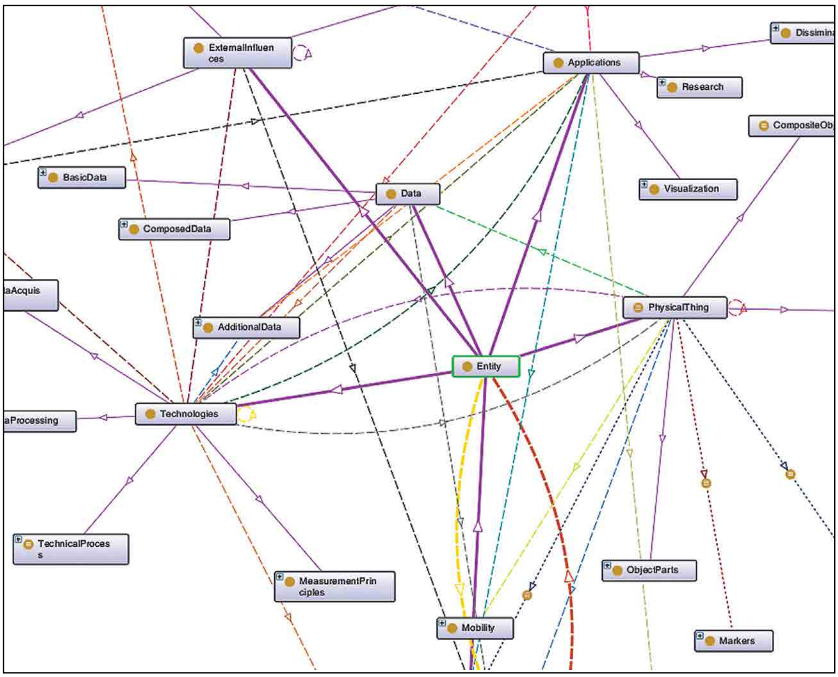

Figure 9.1. A section of the complex graph of the COSCH^{KR}.
A larger version is available at https://coschbook.wordpress.com/9-2/.

COSCH^{KR} Ontology

COSCH^{KR} draws on the developments in the semantic and knowledge technologies within the Semantic Web framework (Berners-Lee et al. 2001). The knowledge model is an OWL 2.0 (Horrocks 2005) ontology-based model. Figure 9.1 illustrates the complexity of the knowledge model by showing a small section of the entire graph. It represents only the second level of the hierarchical structure of the ontology. The taxonomical hierarchy has on average five levels. In addition, figure 9.1 displays twenty-three classes, whereas the entire ontology contains more than 750 classes. Although there are some interrelations displayed by connecting lines and arrows, the figure does not show the inference rules binding the classes together and allowing the retrieval of individual recommendations.

The following sections detail the development of the knowledge model. In the first section the methodologies in developing the ontology and the issues faced during the development are discussed. The second section presents how the knowledge contents were captured to build up the ontology-based knowledge model COSCH^{KR}, which itself is presented in the third section, which also elaborates different semantic constructs inside the ontology.

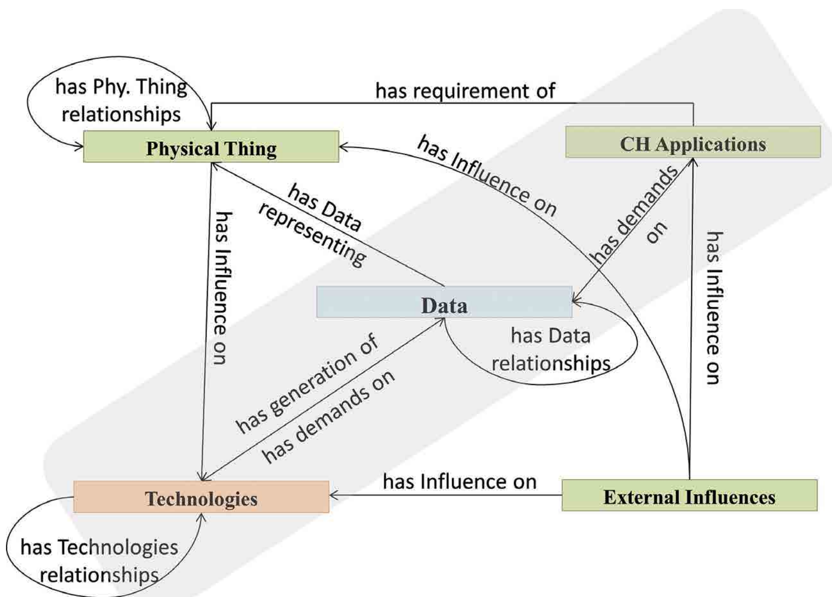

Figure 9.2. Five top-level classes of COSCH^{KR}.

Considerations for Ontology Development

The build-up of the ontology started with agreement on the necessary upper-most classes of the ontology, including natural language definitions of these classes. The top-level structure consists of five classes interrelated through five properties (see fig. 9.2): (1) Physical Thing (Boeuf et al. 2013), (2) CH Applications, (3) Data, (4) Technologies, and (5) External Influences. The first four being the obvious ones needed for generating data. The intention was to keep the ontology in line with the definitions of CIDOC-CRM in order to keep the option of cultural heritage knowledge hubs embracing the standards of CIDOC-CRM. For example, the class *Physical Thing* in COSCH^{KR} can be linked to CIDOC-CRM E18 Physical Thing with the relationship "sameAs" if required. The requirement of the fifth component "External Influences" was included as the data content and quality required for a particular cultural heritage application and Physical Thing is not only affected by the characteristics of the material cultural heritage or the characteristics of the recording technologies, but also through other external influences such as environmental conditions in which the material cultural heritage needs to be recorded or the available budget, which might affect the selection of a technology.

Content Capture

Through an evaluation of the competences available within the European COSCH network three representative case studies were selected, which cover typical cultural heritage applications in the spectral (revelation of a painting's underdrawing), the spatial (deformation analysis, see below), and the visualization domain (digital 3D reconstructed models, Pfarr-Harfst and Wefers 2016). These case studies formed the basis for discussions with experienced experts to develop a class structure and dependencies, and most importantly, inference rules that link the various classes. Only through discussions with these experienced experts was it possible to develop a reliable and broadly based ontology. The experts were asked to explain the project and workflow in their case study. The workflow had to be dismantled and broken down, for example into applied instruments, instrument parts, and accessories. Workflows, which are accepted or standardized within the specific domain, especially needed accurate discussion, as the underlying decisions are linked to technical principles for example, which have to be structured and integrated in the ontology.

At the very beginning of the development of the ontology, the COSCH community established a core group responsible for collecting, managing, and structuring knowledge from the relevant expert groups. The core group was also responsible for defining a common vocabulary. It developed theoretical concepts on the basis of the collected unstructured knowledge through questionnaires and discussions.

These theoretical concepts were represented through respective axioms and theorems. The selected case studies were used to harmonize the collection process of information and to structure the information and knowledge. They also facilitated discussions with the humanities experts involved, as well as the spectral and spatial recording domains, in order to make reference to their work in our discussions.

Questionnaires were applied to ask for the technical and contextual details of spectral and spatial recording approaches in various humanities projects. For each recorded material cultural heritage object with similar physical characteristics and application purposes one questionnaire had to be completed. The original version of the questionnaire consists of twelve main questions with subordinate questions asking, primarily, for technical details,[4] including:

1. spatial and spectral technique/s chosen
2. name of the cultural heritage object or site
3. aim of documentation
4. level of resolution / uncertainty required
5. details for the data collection for either: (a) spatial data (b) spectral data
6. size of the documented cultural heritage object or site
7. shape of the cultural heritage object or site
8. appearance of the cultural heritage object surface
9. whether it is static, moving, movable, transportable
10. budget allocated
11. reasons behind the selection of the technique/s
12. fulfilment of the initial needs by the selected technique/s.

The completed questionnaires supported the analysis to structure the content, to define work areas through the determination of relevant terms and vocabularies, and to identify contact persons having a specific expertise and being available for discussions and feedback. It should be stressed that the approach of using questionnaires does not provide for the collection of knowledge which is already structured and ready for the integration into the ontology (see below). In contrast, the specific content related to one material cultural heritage object and application, which is described within the completed questionnaires, gives evidence for structuring the theoretical concepts included in the ontology.

4 http://www.cosch.info/documents/10179/144419/COSCH_KR_questionnaire.doc/7645d217-4666-4394-833b-cde0a0492bdf.

The COSCH^{KR} Ontology—Classes and Rules

Figure 9.2 represents the five top-level classes of COSCH^{KR}. Each has its own role within the knowledge model that defines the existence and importance of these classes. Additionally, they share relationships with other classes establishing a base for the formulation of inference rules. Finally, these inference rules are used to deliver recommendations for optimal recording strategies for specific material CH and applications.

Classes of COSCH^{KR} Ontology

Classes within the green strip shown in figure 9.2 represent the core part of the knowledge model. The class *CH Applications* describes the most common research questions of cultural heritage domains related to spectral or spatial data through their requirements around data content and quality. The data content and quality is described within the class *Data*. Technologies within the class *Technologies* are described through their capabilities of generating data. Therefore, the axis "Applications → Data ← Technologies" forms the core of COSCH^{KR}. The other two classes *Physical Thing* and *External Influences* provide conditional semantics that restrict or support a certain acceptable technical strategy.

Each of the five top-level classes includes a knowledge description regarding the class:

- The class *Technologies* encompasses the technical process, measurement principles, tools/instruments and the way they are set up to generate or process data. They are represented through sub-classes where each sub-class contains semantic descriptions that represent and/or support their best practice and limitations through their semantic characteristics encoded by the inference rules. The class *Technologies* includes four sub-classes:
    - *BasicDataAcquisition* includes instruments and tools and their required setups to record digital data of material cultural heritage. The class is further broken down into sub-classes: (i) *Tools*—representing instruments and accessories and (ii) *MeasurementSetups*—representing the required setups of these instruments and accessories.
    - *MeasurementPrinciples* includes the principles that govern the instruments. In most cases these measurement principles decide the nature of data generated in terms of quality. They play a vital role in prescribing the proper technological solution(s). The class is further broken down into (i) *Electro-Optical*—where the principles take patterns encoded in the optical propagation and their interaction with the capturing sensors. The class includes *AngleMeasurement*, *DistanceMeasurement*, and *PointVariation* (each are presented through

their respective classes) and (ii) *Optical*—where the principles consider the behaviour of the characteristics of surface reflectance of cultural heritage objects to the optical propagation. The sub-classes within include *CentralProjection*, different projection mechanisms as sub-classes of *ProjectionMechanism* (*Area-Based-Projection*, *Line-Based-Projection*, and *Point-Based-Projection*), *TriangulationPrinciples* (each are presented through their respective classes). Both classes share the principles *AngleMeasurement* and *PointVariation*.

  - *DataProcessing* includes processing tasks and algorithms (represented by the classes *Tasks* and *Algorithms* respectively) through which the data acquired with tools and instruments are altered until they fit to the cultural heritage application.
  - *TechnicalProcess* includes classes describing the complete technical process of data acquisition and processing, preparing the data for the specific purpose of the cultural heritage application. For example, *StructurefromMotion* is a class under *TechnicalProcess* that requires *Camera* (sub-class of *Tools*) with certain setups (sub-class of *MeasurementSetups*) and data processing tasks and algorithms (sub-classes under *DataProcessing*) to generate the 3D data required by the Application (sub-classes under *CHApplications*). These requirements are encoded inside the class representing Structure from Motion through inference rules.[5]

- The class *Data* includes all possible digital/analogue data and document types that are either generated or used to process existing/generated data to achieve the results required by the cultural heritage applications. The class contains three basic sub-classes: (i) *AdditionalData* are information represented by data that may or may not be in a digital format but do not fall under a conventional data category such as oral, visual or textual information, (ii) *BasicData* includes the raw data acquired by the recording instrument and have to be processed further to make them appropriate for usage, and (iii) *ComposedData* includes data that have been processed for the actual cultural heritage application.
- The class *CH Applications* subsumes cultural heritage research questions applying to spectral or spatial data. It determines the required data quality and content. The class is further broken down based on the data requirements

5 The class *StructurefromMotion* is already included in the ontology, however, it is not modelled in depth. Therefore, it will not be included in the description of section 4.

of the applications. Currently there are three sub-classes that in broad terms require different data types: (i) *Dissemination*, (ii) *Research*, and (iii) *Visualization*. The sub-classes under *Research* in general require higher data quality than that of the other two classes. The applications that encode the data requirements presented in this chapter—*DeformationAnalysis* and *RevelationOfUnderdrawing*—are specializations of the class *Research* and demand high-quality data (see below).

- The class *Physical Thing* represents the main subject/object to be measured (in our case it is material cultural heritage). COSCH^{KR} does not define these objects as their real world counterparts. On the contrary, they are defined through their physical and optical characteristics that stem from the measurements and the data that have been recorded for the objects. For example, churches do not have a pseudo-representation through a class "Church" inside the class *Physical Thing*. Therefore, they cannot be asserted as "Church." They are asserted as a composite object (under sub-class *Composite Objects*) as they are built-up of different materials having different physical and optical characteristics (e.g., low surface reflectivity, light colour).
- The class *External Influences* has similar technical implications to the class *Physical Thing*. It defines constraining semantics which effect the recommendations of the technologies. They include physical and optical characteristics (such as lighting conditions) and project limitations such as budget, human resources, or available space for measurement, access, and similar external conditions and factors.

The Rules of COSCH^{KR} Ontology for Inferring Knowledge

The classes within COSCH^{KR} are associated with inference rules, which cut across the other classes defined through the top-level classes. For example, a sub-class within the class *CH Applications* is constituted through an associated rule describing what kind of data are needed, so cutting across the sub-classes of the class *Data*. An example of such a rule is:

> **CH Application (Revelation of Underdrawing)** has Requirement on Data (2D_Data)

This rule states that the cultural heritage application of revealing an underdrawing of an artwork requires 2D data (e.g., an image). This rule is further supported by other rule(s) such as:

> **Application (Revelation of Underdrawing)** has Requirement on **Penetration (Paint Pigments)** at the **Surface of Artwork (Physical Thing)**

In combination, both rules imply that recording an artwork (which is a *Physical Thing*) for revealing the underdrawing (a *CH Application*) requires images (*2D_Data*) with certain spectral wavelengths, which could penetrate paint pigments of an artwork.

From a technical point of view within the sub-classes of *Technologies*, *Multi-Band-Imaging,* or *MultiSpectral-Imaging* are sub-classes of the *TechnicalProcesses* (*Technologies* ⟶ *TechnicalProcess* ⟶ *MultiBand-Imaging/MultiSpectral-Imaging*) that generate images (*2D_Data*) but would require technical components (e.g., filters, sensors) that can capture wavelengths penetrating paint pigments on the surface of an artwork. Therefore, such a technical process should consist of instruments or instrument components that have the capabilities to record spectral ranges penetrating the paint pigment. Furthermore, the physical characteristics of a paint pigment imply whether specific spectral ranges could penetrate it. Near infrared radiation of 700 nm to 2500 nm is expected to be able to penetrate paint pigments that do not contain inorganic elements such as metals. In such a case, user input is required to provide information about the nature of paint pigments of the artwork. The assertion of paint pigments is then inferred using the inference rules of relevant technologies (*Multiband* and *Multispectral Imaging*) defined inside the ontology. For example:

> **Multiband Infrared Imaging** uses **Instruments** that generate **Images** with Spectral Range of **Near Infrared**

and

> **Near Infrared Radiation** is Technical Characteristics of **Instruments** that **penetrates CH Object Surface** with **Organic Paint Pigments**

If the user asserts the paint pigments as organic then COSCH^{KR} will infer that the

> **Multiband Infrared Imaging (Technical Process)** is suitable for the **Revelation of Underdrawing (CH Application).**

A Case of CH Application: Deformation Analysis

Case studies are not only used to enrich the knowledge model but also to verify the inference mechanism and the results generated by the mechanism. First, a case study was selected that dealt with waterlogged wood samples that were recorded in 3D before and after conservation treatment to define the influences of various conservation treatments on the shape of the waterlogged wood samples. Technically speaking, a geometric deformation analysis was performed.

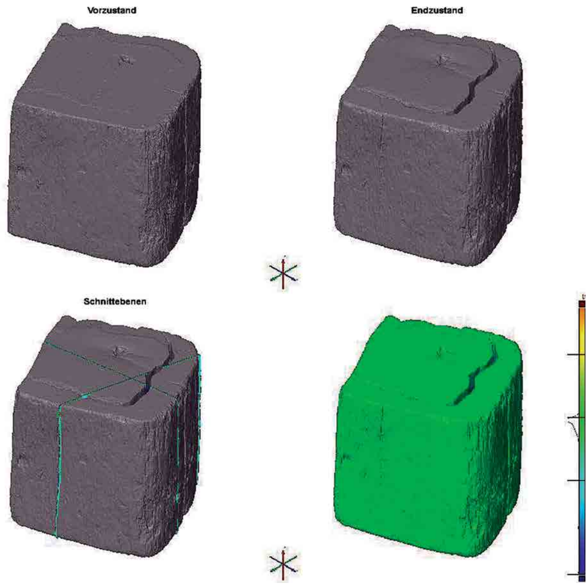

Figure 9.3. 3D models of one waterlogged wood object. The shape before and after conservation treatment and the spatial differences as well as section planes are shown. The model is available for viewing at https://coschbook.wordpress.com/9-2/ and www.rgzm.de/kur.

The analysis was carried out within the research project "Massenfunde in archäologischen Sammlungen"[6] (Mass Finds in Archaeological Collections) of the Römisch-Germanisches Zentralmuseum (RGZM).[7]

The physical CH objects of interest are samples from different time periods having a minimum size of 100 mm × 60 mm × 60 mm (fig. 9.3). The material condition of the samples before conservation treatment was an important issue as the archaeological waterlogged wood samples had a dark brown to black appearance and were partly shiny. The translucent and reflective surface of the untreated samples had an impact on the data quality. However, this impact was reduced to a minimum through careful towelling of the samples before recording. Another crucial factor was the high number of samples: all in all 777 objects were recorded before and after treatment. As regards data requirements for such analysis, the nature of data first depends on the surface characteristics of the objects and then the nature of application. Deformation analysis will always require high-quality spatial data, so precision and resolution are necessary requirements for data accuracy. Since the deformation analysis needs to be analysed in every direction and on every side of the object, this CH application will only be served with 3D data of the objects of at least two eras.

6 http://www.rgzm.de/kur/.

7 http://web.rgzm.de/.

These conditions are defined within the relevant classes inside COSCH^{KR}. The class *CH Applications* triggers the entire inference process. Therefore, the definitions of applications inside this class set the tone for the rest of the process. The class *DeformationAnalysis* (*CH Applications* ⟶ *Research* ⟶ *ChangeDetection* ⟶ *DeformationAnalysis*) is defined through the following rules:

requirement on data **3D Data**

requirement on data **High Accuracy, Resolution, and Precision**

The first rule demands that data must be 3D data. The second rule demands that the application requires highly accurate, precise and high-resolution 3D data (= high-quality data). These two rules are then inferred against the rules defined under classes and sub-classes of *Technologies* to find out which technologies are able to generate the necessary 3D data.

The technologies are compared first through their principles under *Measurement Principles* (sub-class of *Technologies*) to check which generate 3D data. Then they are checked against instruments and the technical processes involved to determine whether they are capable of generating high-quality 3D data (including accuracy, precision, and resolution). With the first inference process, the machine suggests *Laser Scanning* and *Structured Light 3D Scanning* (both are sub-classes of *Technologies*) as they are capable of delivering high-quality 3D data based on their respective principles used: Angle/Distance Measurement Principles for Laser Scanners and Triangulation Principle for Structured Light 3D Scanners. Both principles are capable of generating high-quality 3D data. This is defined through:

Angle/Distance Measurements generate **3D Data** with **high** or **medium** or **low Accuracy**

Angle/Distance Measurements generate **3D Data** with **high** or **medium** or **low Resolution**

Angle/Distance Measurements generate **3D Data** with **high** or **medium** or **low Precision**

Triangulation generates **3D Data** with **high** or **medium** or **low Accuracy**

Triangulation generates **3D Data** with **high** or **medium** or **low Resolution**

Triangulation generates **3D Data** with **high** or **medium** or **low Precision**

Laser Scanners use **Angle/Distance Measurements**

Structured Light 3D Scanners use **Triangulation**

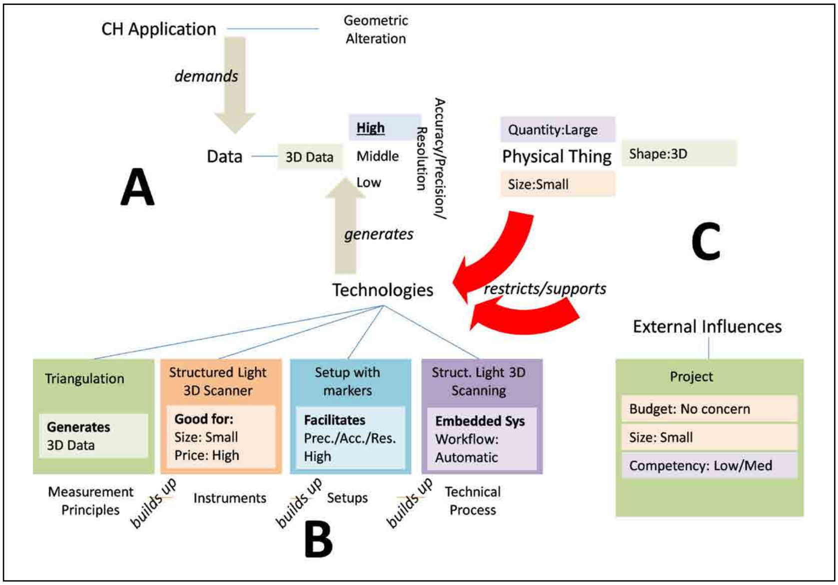

Figure 9.4. The inference mechanism (A) demands on data: deformation analysis demand high accuracy 3D data, (B) generation on data at technical level through technologies first through the principle then instruments adapting to the technical process (C) the restrictions provided by CH objects and other external influences on the technologies. A larger version of this diagram is available at https://coschbook.wordpress.com/9-2/.

The inference mechanism first considers the rules relevant to the data (see fig. 9.4). It should be noted that the technical questions relating to the requirements around data or to technical solutions are not presented to the users. They are inferred through the rules defined inside the class. However, if there are some requirements that decide the type of data, the user will be asked for input. For example, the question about the shape of the object can sometimes decide the required data type (see fig. 9.5, where the red boxes demand user inputs and grey boxes represent inferred information), and so the question will be asked. Until this point, the interface raises queries that address the quality requirement around data but hereafter it raises queries related to other issues. These issues are generally raised to check their impact on the technologies and their underlying solutions. For example the material of the CH object, the surrounding of the CH object, lighting conditions and similar factors which have an impact on the selection of any particular technical solution. Here, the platform would ask for input from the user in order to make further decisions. For example, asking questions regarding the size and number of CH objects, budgets, technical competence, have profound effects on what instruments are selected. In this case the rules defined at

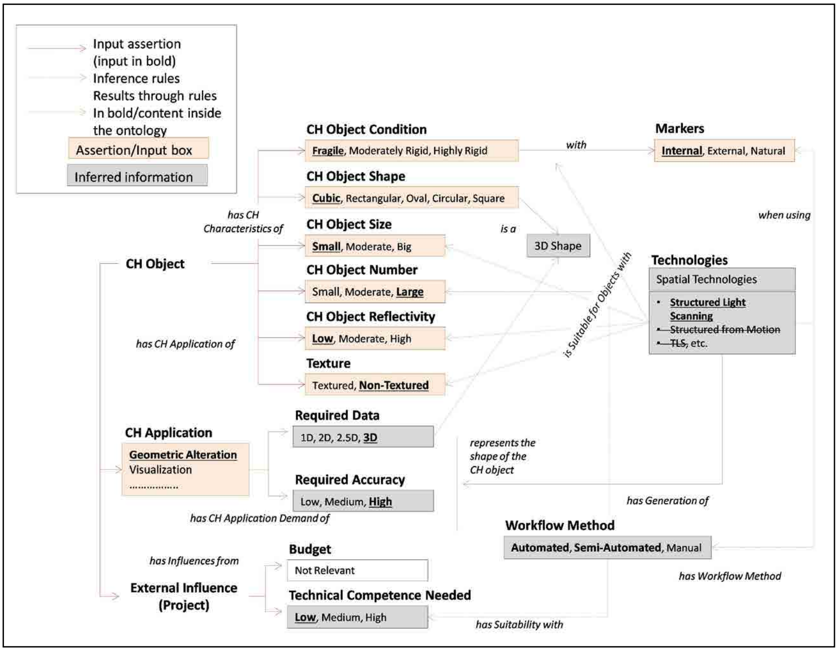

Figure 9.5. Simulation of a GUI for the case study in conservation of waterlogged wood. The red boxes represent the user input and the grey boxes represent the inferred information. A larger version of this figure is available at https://coschbook.wordpress.com/9-2/.

the end will skip Laser Scanning (and its main instrument Laser Scanners) because they are not suitable for scanning small and many objects with the required resolution to identify the expected deformation. Since the budget was irrelevant in this case study, Structured Light 3D Scanning (more specifically an Industrial System) and the instrument Structured Light 3D Scanner were recommended. The recommendation would be completely different if for example budget comes into play or one single large object needs to be scanned or the CH application is different, requiring no high-quality data. These parametric-dependent diversions of recommendation when new constraining parameters are included are indications of the flexibility that semantic techniques bring. The quality of recommendations inferred entirely depends on the quality of parameters and inference rules which are encoded inside. Likewise, when these parameters and inference rules are defined with a high degree of exclusiveness, the chances of recommending a single optimal technical solution become high. It should, however, be noted that COSCH^{KR} is under development and in the course of time more rules and parameters will be added to it, and this will certainly improve the likelihood of generating useful recommendation(s).

Conclusions and Future Work

The COSCH^{KR} ontology practically encodes inference rules and can be used as a tool to represent the knowledge of all disciplines and experts involved in the digital documentation of material CH. Other reasoning engines within the Semantic Web technologies which were developed to reason those encoded rules exhibit serious limitations due to aggregating complexities when executing the inference. In short, existing engines lack the capabilities to infer the complex aggregated semantic descriptions defined at the conceptual level. Therefore, this mechanism is under development to translate these complex aggregated inference rules into Prolog statements, to be able to infer the recommendations. Last but not least, a web service will be developed that will infer and retrieve knowledge through an interactive user interface.

To be able to publish a convincing COSCH^{KR} platform the underlying ontology has to have a considerable number of CH Applications integrated within it. Therefore, one of the major tasks is to identify, structure, and encode a large number of typical CH Applications. As more and more information about CH Applications are included through their relevant classes, relations, and rules, the regular task of structuring the ontology will ease off.

As soon as the first spectral, spatial, and visualization CH Applications are integrated and interwoven, we intend to hand over the development and maintenance of this ontology to a wider community. The ontology will thus be publicly available for use. The entities inside the ontology will be documented to make clear the reason for their existence inside the ontology and also how they are interrelated within the ontology. We also intend to develop Application Programme Interfaces (API) to access and use the ontology for any future developments based on the ontology. Cultural heritage stakeholders in particular should be interested in maintaining and developing this ontology as the preservation of material cultural heritage will be supported through digital surrogates which fit the requirements of the cultural heritage experts. This will address the issue of sustainability and use of the ontology in the long term. Cultural heritage stakeholders' archives will also contain more reliable and durable digital copies of their material cultural heritage.

Chapter 10

COMMUNICATING INTERDISCIPLINARY SCHOLARSHIP: CONCLUSIONS FROM COSCH

ANNA BENTKOWSKA-KAFEL
With contribution from FRANK BOOCHS

ABSTRACT

The study of cultural heritage requires the expertise of many disciplines as different as history and optical science. Each discipline brings its discrete research methods and know-how. Complementary knowledge is gained, gradually, through effective collaboration, which is not always easy. The articulation and communication of respective research questions, ways of addressing these questions, and expected outcomes, are a challenge in all collaborative projects. This concluding chapter discusses how the COST Action, Colour in Space in Cultural Heritage, has addressed and managed this challenge, through the case studies described in the present book and other activities. The authors draw conclusions from COSCH research activities and note some general points that bear on the success of diffusion of interdisciplinary research and its future.

Keywords: interdisciplinary research, communication, cultural heritage, science, optical technologies, COSCH

> It is everyone's responsibility to improve interdisciplinary communication, something that starts and ends with willingness, plenty of patience, and an open mind.
>
> (Darren Kocs 1993, 1060)

The study and documentation of cultural heritage require the expertise of many disciplines as different as history and optical science. Each discipline brings its discrete research methods and know-how. Complementary knowledge is gained, gradually, through effective collaboration. The articulation and communication of respective research questions, ways of addressing these questions, and expected outcomes, are challenges common to all collaborative projects. This concluding chapter discusses how the COST Action, Colour in Space in Cultural Heritage (COSCH) has addressed and managed these challenges, through the case studies, described in the preceding chapters, and other research and training activities conducted between 2012 and 2016. We reflect on earlier projects that also shared the goal of "bridging the gap" between disciplinary approaches and mindsets, specialist research methods and tools, while showing the distinctive approach of the COSCH network. We draw conclusions from COSCH's four-year engagement in the interdisciplinary debate by noting general points that, in our view, bear on the success of future research and its diffusion.

On the Perceived Notion of "Two Cultures"

"The scientist has the habit of science, the artist the habit of art."[1] The concept of "two cultures" has persisted since it was forcefully proposed in the 1950s. It is not only widely understood, but also cultivated in the English-speaking academia, as evidenced by a recent, double issue of *Interdisciplinary Science Reviews* (James 2016) that elaborates on its legacy. Originally coined by C. P. Snow (1956) to convey "a gulf of incomprehension" between scientists and "literary intellectuals" (Snow 1959), the phrase became a byword for the perceived irreconcilable differences between science and technology on the one hand, and arts and humanities on the other. Snow spared no criticism for educated people being proud of their ignorance of science. Scientists, on the other hand, often find it difficult to accept the philosophical and speculative nature of academic cultural discourse. "To . . . an engineer every problem has a solution."[2] The value of arts and humani-

1 Flannery O'Connor, *Mystery and Manners: Occasional Prose*, Selected and edited by Sally and Robert Fitzgerald, New York: Farrar, Straus and Giroux, 1957, p. 65.

2 Oleg Vishnepolsky, "Best People Get Fired for Cause: Tragedy of the Modern World," 12 December 2016, online at https://www.linkedin.com/pulse/best-people-get-fired-cause-tragedy-modern-world-oleg-vishnepolsky, accessed 18 December 2016.

ties scholarship is in the quality of a critical argument and the transparency of its sources; humanities research does not aim at solving a problem or proving something. Historical interpretation of the past, of which the study of material cultural heritage is a manifestation, is always incomplete and therefore tends to be ambiguous. Documentation should reflect this. Truth and accuracy are expected from hard science (Graff 2015, 38). Science and technology are empirical and validated through repetition of operations that yield same results. In contrast, arts thrive on creativity, unpredictable originality, and the uniqueness of the creative process. Material heritage, being an expression of culture, cannot be measured through spatial and spectral optical means alone. For example, an early application of 3D laser scanning, stereomicroscopy, and image processing to the analysis of Rembrandt van Rijn's painting *The Tribute Money* (National Gallery of Canada, Ottawa) has revealed that the artist's signature in monogram and date 1629 were applied at the same time (Baribeau et al. 1992, 73). The results of this scientific examination are valuable, but insufficient to confirm either the attribution of the painting to Rembrandt or the year it was made. A combination of other complementary methods is necessary, including the interpretation of artistic and historic evidence. Our network COSCH faced up to the challenge of making multidisciplinary collaboration more cross-disciplinary (for further discussion see chapter 1).

While acknowledging that disciplinary expertise demands the highest possible specialism, COSCH's prime objective was to push the limits of cross-disciplinary research through direct integration of discrete research practices in the case studies, described in the preceding chapters, and other activities. In the second half of the Action the thematic working groups were mixed to help this integration. Can such interdisciplinary, collaborative research be communicated to the wide range of stakeholders involved in the study and preservation of cultural heritage, without compromising disciplinary specialisms and without resorting to popular science? This book represents an endeavour to do just that.

The discourse of the arts and humanities is to some extent approachable by scientists and engineers. This cognitive position is rarely reciprocal, however. COSCH was a trans-domain COST Action (TD 1201) in Materials, Physical and Nanosciences. How can a humanities scholar, or other non-scientist, professionally involved in cultural heritage, contribute constructively to research into the material and physical sciences pertaining to cultural heritage, much dependent on modern digital technologies and computer science? Although non-technical expertise is critical to cultural heritage studies and is valuable in conservation projects, the interaction between a heritage scientist and the object curator has traditionally been typically limited to the latter's selection of objects in need of treatment, and acceptance of the results of the technical examination; its documentation was rarely shared with non-scientists.

Active engagement in the scientific process poses a problem for many historians and other cultural specialists. Art historians, for example, have a notorious reputation of lagging behind other disciplines in the adoption of computing; its benefit is by no means universally recognized. "The art history community is ambivalent about the value of digital research, teaching, and scholarship," reported a major survey (Zorich 2012, 8). The larger community of humanities scholars seems unable to shed a similar reputation established, *inter alia*, by an influential report from the Summit on Digital Tools for the Humanities, held at the University of Virginia in 2005, which accepted (Frischer and Unsworth 2005, 4) that "only about six percent of humanist scholars go beyond general purpose information technology and use digital resources and more complex digital tools [such as GIS and 3D visualization] in their scholarship." This and many later reports recognize the humanities preference for rather conservative research practices and solitary research, above technological innovation and collaboration. The latest research by DARIAH-EU (Dallas et al. 2017) into research practices in the arts and humanities indicates widespread use of digital tools, but predominantly as basic as word-processing and consultation of online resources.[3]

A convincing, evidence-based case for the acceptance of more advanced digital research methods and their wider adoption by the arts and humanities communities, as one of means of interdisciplinary engagement, must continue to be made. With increasing success initially in North America and the Anglophone world, but gradually growing elsewhere, funding initiatives from the National Endowment for the Humanities (NEH) in the USA, and from the Arts and Humanities Research Council (AHRC) in the UK, have served to heighten interest.

Interdisciplinary Precedents to COSCH

An application of a particular spectral or spatial analytical/recording technology to material cultural heritage is proven beneficial when it enables new insights into the studied object; ultimately supporting its conservation, public display, and other forms of communication and dissemination. Examples are plentiful. Multispectral imaging made it possible to reveal two texts of previously unknown treatises of Archimedes, concealed, alongside his five other treatises, underneath the text of later Byzantine prayers (Archimedes Palimpsest Project 2000–2008). In the areas covered with modern forgeries and where the ink was too faint, and the parchment too stained for the multispectral imaging to work, X-ray fluorescence using synchrotron radiation was applied successfully. These outcomes were

3 We wish to thank Orla Murphy for drawing our attention to this particular area of DARIAH's research presented at https://dariahre.hypotheses.org/285.

a result of a long collaborative research project involving the owner of the palimpsest, the Walters Art Museum in Baltimore, USA, where it is housed, the Rochester Institute of Technology, and the Stanford Linear Accelerator Center of the University of Stanford (now SLAC National Laboratory); the project credits some thirty scholars, conservators, and other contributors. The Digital Forma Urbis Romae Project (from 1999) was another exemplary collaboration between the same university's Department of Computer Science and the Department of Classics, the Sovrintendenza ai Beni Culturali del Comune di Roma, with dozens more scholars and many volunteers contributing in the USA and Rome. The project involved the spatial recording, using laser range scanners, of 1186 extant marble fragments (some 15 per cent) of the map of Rome in the early third century (approx. 18 m × 13 m) which originally decorated the interior of the Templum Pacis in Rome. To enable as complete digital reassembly of the fragments as possible, the available historic drawings of lost fragments were also digitized. All this material has been catalogued in a database, alongside the 3D records of the fragments and inscriptions, and in-depth historical information. The cutting-edge technology of the 1990s has aged, superseded by more robust systems, better data processing algorithms, higher resolution scans, but the methodology of the Forma Urbis Romae project and its transparency remain exemplary. Errors in 3D scanning, the noise introduced, missing data, and automated digital "repairs" that could otherwise give a false impression of the original artefacts are illustrated and explained. Some sixteen years on, the data sets and metadata from both projects remain freely accessible online and, as scholarly resources, are still indispensable. Based on this exemplar, the sustainability of interdisciplinary collaboration is clear-cut on the grounds of its continued scholarly value.

Unlike these two projects, COSCH did not start with the digitization of particular historic objects in mind. Scientists, engineers, and providers of spatial and spectral solutions (mostly academics) with previous experience in collaboration with cultural heritage scholars and professionals, proposed an agenda for enhancing instruments, their calibration, precision of measurements, data acquisition and processing, and the fusion of multimodal data. The focus was on applications to cultural heritage. The case studies, described in the preceding chapters, were designed collaboratively, and carried out in discussion with the COSCH group at large and under scrupulous peer-review.

There have been notable earlier scholarly projects that, like COSCH, sought to perfect the applications of digital technologies to the study and documentation of cultural heritage. Those involving 3D digitization included CARARE, 3D-COFORM, 3D-ICONS contributing the relevant know-how and 3D content to Europeana Collection, and V-MusT—all with a strong emphasis on international collaboration for online access to virtual surrogates of cultural heritage, and on education;

building centres of excellence and providing advice and training. No comparable project served as a direct model to COSCH's concurrent consideration of spectral and spatial technologies and algorithms, with the potential for their integration in recording practice and in the semantically structured representation of relevant knowledge. COSCH was not committed to contributing digital content to existing European repositories. However, by designing COSCH case studies (chapters 2–8) and the $COSCH^{KR}$ knowledge representation (chapter 9) we were able to interact with broader communities of heritage practice, and communicate our research to other audiences. Some data sets, 3D visualizations, and other outputs of COSCH studies have been made freely available for use and further research.

Every large-scale, international collaborative project faces a challenge of making internal and external communication effective. Has COSCH benefited from lessons in communication from earlier research collaborations? What makes communication effective is rarely studied by the cultural heritage projects themselves. Learning through trial and error and benefiting from individual experiences tends to be a prevailing *modus operandi*, and was such for COSCH. Despite the wealth of internationalized and globalized modern research, an effective universal strategy that could guide new collaborations is not available. Is such guidance possible? Looking at examples from the history of twentieth-century interdisciplinary collaborations, Graff (2015, 5) concludes: "There is no single path to interdisciplinarity, no single model, no single standard for successful development. The process and results vary across disciplines and clusters. Like disciplines, interdisciplines are diverse in paths, locations, relationships to disciplines, organization and institutionalization." The awareness of these differences makes communication more attentive to individual needs and expectations.

The COSCH Experience of Interdisciplinarity

COSCH was established to facilitate the discussion of cross-disciplinary research into applications of optical technologies to material cultural heritage. It was strictly an international networking initiative and unlike the aforementioned projects did not benefit from direct funding of research. The COSCH Memorandum of Understanding (2012) stipulated an overall direction for the Action, the starting point and ultimate goal, mainly from the scientific and technological perspectives. No specific interdisciplinary tasks were defined, except the generic objective to develop a common understanding through a dialogue. The rationale behind COSCH and its interdisciplinary purpose have been summarized as

> [O]ne of the latest international and interdisciplinary efforts in perfecting documentation of extant material cultural heritage. The emphasis [was]

> on non-invasive documentation, based on accurate recording of colour and geometry of objects, using multispectral and 3D imaging. Despite recent advancements in colour science and optical measuring techniques there are still many unresolved questions concerning the lack of shared standards in colour and shape measurements. There is no common understanding of best practice. Access to high quality 3D records, based on precise surveying methods, is limited—this hinders the understanding of benefits and limitations of such techniques, constricting their wider adoption in professional museum and heritage practices, and other areas of study. COSCH [drew] on earlier interdisciplinary research and [relied] on strong engagement of users from across cultural heritage domains. COSCH [was] designing new case studies and developing new digital tools for enhanced, *shared understanding and application of spatial and spectral documentation*. (Boochs et al. 2013; Boochs et al. 2014, 713; emphasis added)

We, the authors, a scientist and an art historian, both academic scholars with years of experience of collaborative research, were elected to Chair and Vice-Chair COSCH. In a typical research project its team and skills are defined prior to the award of funding. Participation in COSCH was voluntary, however, and, with the exception of a core group of original proposers, could not have been predicted, impacting on our ability to plan and deliver the work in accordance with the original objectives. We expected the active participation of as many relevant disciplines involved in the study and documentation of cultural heritage as possible. The biographies of COSCH participants are representative of the extraordinarily diverse backgrounds (see p. 263 and *COSCH Who's Who* 2012–16). The participation in COSCH was augmented from 137 researchers from twenty-five countries (by July 2013) to 237 researchers from twenty-eight European countries by November 2016. It was assumed that, prior to joining, each new participant had familiarized him- or herself with the principles of COST Actions, and with the COSCH objectives and organization of work, laid out in the Memorandum of Understanding (COSCH MoU 2012).

The process of achieving the desired outcomes through the collaborative effort involved several stages. It started with the assumption that the complexity of the desired tasks might be reduced by restricting the number of technological specialisms and by clearly defining their scope—spectral and spatial applications, algorithms and data processing, alongside material surface analyses and data visualization—with the expectation of transferability of the scientific insights gained to different disciplines. However, the discussions revealed an enormous complexity of subjects and variations in individual understanding of technology even within a single discipline. The extent of disciplinary complexity obscured the broader picture and what we had assumed was a clear chosen path. The importance and characteristics of technological research were assessed in different ways. At the next stage, the strongly interdisciplinary groups started to establish the connections between technology and fields of application, but without fully understanding how they operate. The significance of theoretical work, that underpins all research, could not be ignored. Finally, through practical work and more discussions, the group began to develop a shared view of problems and solutions.

COST Actions are open to new members in the course of their running, subject to eligibility (COST Vademecum 2016). A new researcher joining the group was seen an indication of the recognition of COSCH's work and purpose. In accordance with the COST emphasis on wide participation, COSCH was open to researchers from any field, at any stage of their career, from universities, research centres, public and private organizations, and commercial companies in any of thirty-six eligible countries. What such a wide and varied membership means in terms of the diversity of tongues and minds is not difficult to fathom. Not only the otherness of science and technology from the arts and humanities was apparent, but also differences between individual disciplines, and within their various fields, and between the individual researchers representing the same field. The heterogeneity of COSCH researchers was manifest in their individual experience and degree of specialization, education (even the impact of different schools within a discipline), diversity of cultural backgrounds, and personal interests. The interdisciplinary engagement in COSCH was therefore challenging on many levels. The contributors to this volume state, explicitly or indirectly, the intellectual differences encountered when dealing with another research culture. COSCH debates saw different ways of constructing an argument, different reasoning and different conceptualization. Drawing different conclusions from the same facts or scenarios, depending on one's background, was not unusual. "This experience showed that the ways humanities and engineering researchers approach a problem vary profoundly. Cultural differences, not connected to nationality, but to the field of work, represented both an asset for the project and a challenge at the same time" (chapter 7, p. 138).

For many involved in a collaboration such as COSCH a leap of faith is required to embrace another, often unfamiliar discipline, and sometimes not one, but a number of fields. An open mind and a great deal of new learning were required. Arts and humanities scholars who decided to get involved in a COST Action in the area of material science and physics have certainly demonstrated open-mindedness. However, not many archaeologists, art historians, museum curators are capable of fully understanding the scientific and technological complexity of 3D sensing, spectral imaging, algorithms, and data processing. Arts and humanities are more approachable to a non-specialist, but only to a point. One is often unable to help one's own superficial knowledge or ignorance when faced with an unfamiliar area of scholarly research. This ignorance is plain to see by a specialist. Optical technologies, such as laser scanning or structured light scanning, are praised for their unprecedented accuracy of spatial recording. Why do they involve decimation of raw data? Is less data better than more data? Why is a manual repair of the resulting point cloud necessary? Why does imaging of a material object through RTI require the reconstruction of *the object*, with "reasonable reconstruction" considered a good result? (MacDonald et al. 2016, 76). Christos Stentoumis is linguistically more precise, when he writes about multiple view stereo vision (see p. 225) as "the process of reconstructing *the 3D model of an object* or scene [emphasis added] from a set of digital images." In archaeology, art and architectural history and in conservation, the notions of the object, its representation, and reconstruction are very different from scientific research. Each field would probably argue for being more nuanced. In conservation, reconstruction is considered and classified in relation to renovation, restoration, anastylosis, and restitution—depending on the extent of alteration of the original fabric, type of materials used (original v. non-original) and the final result. Reassembling parts of a broken ancient Greek vase (chapter 2) constitutes reconstruction when the missing parts are substituted, or restoration when no such an attempt is made (ICOM-CC Resolution 2008, 2). The same Resolution stipulates that restoration of a single object aims "at facilitating its appreciation, understanding and use. . . . These actions are only carried out when the item has lost part of its significance or function through past alteration or deterioration. They are based on respect for the original material. Most often such actions modify the appearance of the item" (ICOM-CC Resolution 2008, 2). Digital scholarship adds to this complexity by blurring the distinctions between physical and virtual processes. Training in such physical disciplines as archaeology, art and architectural history, the conservation and restoration of cultural heritage naturally prepares one for the extension of practice into the digital realm. This, for example, can be illustrated through a definition of virtual anastylosis in archaeology as "the reordering of available remains digitally to virtually reassemble something that existed in the past. This process makes a 3D model assembling surveyed fragments, present in the excavation site, with elements philologically reconstructed on the basis of historical knowledge and documentation' (AAT 1988–, ID: 300389891).

As COSCH discussions have shown (chapter 1) there is by no means a consensus as to the terminological variations in use. Transparent definitions of terms, in the context of a particular research project or task, are essential. Terms express ideas, decisions, and solutions. No understanding should be assumed, each use must be expressed unambiguously. Another good example can be found in chapter 4 (p. 79): "two snapshots of a detail of a thistle rendered using the Polynomial Texture Mapping (PTM) reconstruction method from an H-RTI recording," dispelling any potential ambiguity, in this particular case, between the object, its representation, and the subject of reconstruction. Far too often mental shortcuts and the convenience of professional jargon confuse the message. The challenge in the interdisciplinary debate is to acknowledge that PTM reconstruction (through digital "stitching" of multiple images of an object to form a single visual representation) and philological reconstruction may have equal cognitive benefits and be not entirely disconnected. An excursion into a modern theory of the image complicates the matter further, while supporting some of the above claims. Elaborating on the linguistics, the code, and meaning of photographic representation, Roland Barthes saw it as a repetition rather than transformation of the source subject matter: "the image is re-presentation, which is to say ultimately resurrection, and, as we know, the intelligible is reputed antipathetic to lived experience" (Barthes 1964, 152).

Clarity of the terms and context of research is conditional to effective communication. As far as interdisciplinary terminology is concerned, Miller (2011, 8) believes that the problem of "translation" is superficial, as any researcher should be able to learn how terms are used in another discipline and use them appropriately. The experience of the COSCH Action was not that simple, however, confirming that to understand the specialist terminology one needs to understand the research culture and practice expressed. Therefore "the problems that interdisciplinary research faces stem [not from terminological issues and miscommunication, but] instead primarily from methodological issues, and in particular from the nature of the answers that different sorts of disciplines are looking for and the different sort of questions that are being asked" (Miller 2011, 9). The awareness of that difference is the first step towards identifying its nature.

Conclusions from COSCH

We would argue that successful interdisciplinary collaboration does not require reconciliation of disciplinary differences, which should be respected. A forum for their articulation and discussion, as provided by COSCH, is beneficial to collaboration. Research thrives on complementary coexistence of disciplines. The biological symbiosis of dissimilar organisms that need each other to function and develop may serve as an analogy. Interdisciplinarity is at risk when attempts are made to convert one field into another, or when a valid expression of knowledge or critique is lost through suppression by another. The topical debate of the observed undisciplining of knowledge through interdisciplinarity (Graff 2015) must respect the equality of varied cognitive positions. The eminent convergence of disciplines through interdisciplinary research, observed by Graff and others, was not experienced within COSCH. A greater coherence of modern methods of investigation, or the cross-disciplinary unimethods, seems more likely, but only after a considerable and prolonged collaborative effort.

Facilitators of Interdisciplinary Communication

COSCH approached the challenge of interdisciplinary communication through different forms of collaboration and discussion, training, internal and external dissemination—this book provides ample examples. "Collaborations are intense, not superficial, relationships," states a report by the US National Research Council of the National Academies, differentiating collaborations from "communication (the sharing of information), and cooperation (in which participants influence the decisions of other participants in a common effort). . . . What they share is the intention of creating something larger than the sum of their parts" (Mitchell et al. 2003, 40–41). The COSCH work towards the formal representation of knowledge relevant to applications of spatial and spectral optical surveying methods in the COSCH^{KR} represented such an intention.

Communication beyond the COSCH network and interaction with a wider community of practice was another objective. COST support was available for a one-off participation in COSCH conferences of experts from countries outside Europe, if and when beneficial to COSCH proceedings. For example, Fenella G. France, Chief of the Preservation Research and Testing Division at the Library of Congress, presented her Division's work on non-invasive hyperspectral imaging of Thomas Jefferson's 1776 draft of the Declaration of Independence and other historic manuscripts in the Library collections (France 2013). Other American experts contributed academic papers and served as peer reviewers to the *COSCH e-Bulletin*, an online journal set up by the network. The COST Trans-domain Action scheme is manifestly conducive to cross-disciplinary collaboration and recognizes its benefits, but does not directly support research. Funding is for networking activities (including travel and subsistence; excluding conference fees). Research is expected to be funded nationally and embedded in the activities of participating institutions. COSCH researchers, particularly those in the early stage of their careers, benefited from the COST effective support of study visits to foreign research establishments. Fifty-six of these, so-called Short-Term Scientific Missions (STSMs), were conducted (COSCH STSM Reports 2013–16), some of which contributed to the case studies described in this book. This kind of facilitation of interdisciplinary research should be encouraged. It enables individuals to conduct research according to their particular interests, in an institution they consider to be leading the field, under the supervision of their choice and scrupulous formal peer review. For COSCH researchers the contacts forged through these exchanges were overwhelmingly positive, enjoyable, and led to planning new collaborative projects. The same can be said about the nature of interaction within the network in general.

As a prerequisite to the technical enhancement of optical digital recording tools and methods, and their potential, wider adoption, COSCH's work was to respond to *actual needs*. The needs had to be identified first and the COSCH case studies were designed to this end. The providers of technological solutions (some engaged in the cultural heritage research practice, therefore "users") reached out to other professionals and scholars. Custodians of museum collections, archaeologists, conservators, and heritage scientists working in museums identified the objects and sites suitable for COSCH research, and facilitated access. Technical examination and reliable methods of monitoring the condition of historic objects were amongst the top conservation needs, alongside other research questions. The study of fragments of the Karabournaki kantharos (chapter 2) investigated how this vase might have looked originally, and what are the benefits and limitations of a hypothetical, 3D virtual reconstruction. The study of medieval wall paintings in the Château de Germolles (chapter 4) was an investigation into the original artist's materials, the composition and meaning of the decoration—all important for deciding upon the most suitable conservation and presentation of the murals. Digitization of selected objects in the Romanian Museum of National History, for online access to virtual surrogates (chapter 6), aimed at alleviating the prolonged closure of the museum to the public, while also introducing the relevant know-how to practitioners in the local museum. The Roman coin case study (chapter 3) tested a wide range of optical recording and visualization techniques and engaged in discussions with numismatists and metal conservators about their evaluation and wider adoption. The number of identified scientific, technological, organizational and societal questions that are yet to be resolved to the satisfaction of the stakeholders will inform the ongoing research and development of the next generation of instruments and procedures.

Live demonstrations of professional practice—organized in the very places where research is conducted, with the possibility of asking questions, by specialists from the same field and the uninitiated alike—were amongst the most effective means of interdisciplinary, scholarly and professional communication of the latest science and technology applied to cultural heritage research. Demonstrations were part of many COSCH meetings. Numerous visits to scientific laboratories included demonstrations of an array of multispectral instruments in action at the SIB Laboratories of the School of Computing, University of Eastern Finland in Joensuu; an interesting application of the LAbScan imaging with VNIR PFD (400–1000 nm) to detect fake banknotes; and a process of automated digitization of botanical specimens from the herbarium of the Finnish Natural History Museum (Digitarium 2010–). At the Institute of Measurement Science of the Slovak Academy of Sciences in Bratislava, a phoenix nanotom® was demonstrated. The system is used in computed tomography (microCT and nanoCT) and 3D metrology. It was used in the elemental analysis of the denarii of Faustina the Elder, and to provide, with varying degrees of success, the ground truth 3D data against which other measurements of the same coins could be compared (described in chapter 3). In addition to the lab demonstrations, visits to museums, conservation departments, and tours of heritage sites, guided by their scientists and curators were organized. They offered opportunities to understand issues in optical recording methods in the context of actual requirements, dictated by the nature of collections, local environment and the condition of the object. This is how we learned first-hand about particular challenges in the conservation of modern art by artists experimenting with materials that have not aged well. We looked at the artworks in question, housed in the Museum of Modern Art in St Etienne, France, where we also found out from their restorers about conservation treatments and discussed how technology may support this practice. In Mainz, Germany, we visited the laboratories of the Institute for Spatial Information and Surveying Technology (i3Mainz) of the University of Applied Science (the COSCH leading institution), as well as the laboratories of the Römisch-Germanisches Zentralmuseum (RGZM). At this archaeological museum we were introduced to digitization projects, such as the periodic recording in 3D of waterlogged historic wood, to monitor possible deformation (see chapter 9). Alongside the discussion of the role of technology in museum conservation practice, we were also able to appreciate the extent of traditional, manual, highly skilled artistic work involved in making material copies of ancient artefacts, ongoing at RGZM for scholarly and educational purposes.

The organization and funding of interdisciplinary work were frequent topics of COSCH discussions. An exemplary model of cooperation would be the RGZM's solution to employ an engineer specializing in geo-information and heritage science, based at the i3mainz university. He teaches students 3D scanning, and other subjects in applied technology, using the museum's artefacts that can be safely moved to the university. The objects and all involved benefit from this collaborative provision of specialist digitization solutions and education at the same time.

A new breed of professional intermediaries, including academic editors, is required to ensure that interdisciplinary research is adequately communicated to expert researchers and students alike. Scholarly communication must satisfy the highest standards of each contributing field, and without potentially compromising any of the contributing knowledge. Scientific papers on technology applied to cultural heritage often lack information about the cultural heritage in question (even as basic as the name, date, and location of the object); whereas humanities papers tend to ignore scientific research into the subject. COSCH authors were sometimes prompted to restore the interdisciplinary balance of the content. Academic publishers have traditionally separated scientific work from cultural subjects. Springer Verlag has an established reputation of publishing science and technology applied to cultural heritage; their outreach to readers within arts and humanities however is limited. It may come as a surprise that this book, with considerable technical content, is published by Arc Humanities Press, renowned for titles in medieval and global history scholarship. The preoccupation of COSCH researchers with science, technology, and cultural heritage provided the desired connections that appealed to this humanities press, which "publishes research that fosters better public engagement in, and understanding of, the past and of the ways in which the contemporary world is linked to the premodern world. Arc Humanities Press is the publishing arm of the Carmen Worldwide Medieval Network, and reflects this learned society's particular interest in international collaborative research, global history, cross-faculty research, and applied research" (source: https://mip-archumanitiespress.org/series/arc/). This kind of openness to interdisciplinary research is needed to encourage the trend.

> The growing role of intermediaries is not simply that of the one-way dissemination of research outputs; it must foster a two-way or multi faceted dialogue between the various stakeholders and support the whole research cycle. (Carter and Paulus 2010, 84).

Training and Learning

In the elaborated version of his critique of two cultures, C. P. Snow (1963) argued that the solution to what is clearly a perennial problem of the widespread ignorance of science is through good and early education. Training and learning opportunities, at all levels, are essential for the future of the field in question. They guarantee direct exposure to interdisciplinary research and are conducive to critical reflection. As the i3mainz-RGZM cooperation shows, the learning environment necessitates the visibility of interdisciplinary research in the first place, and requires effective communication of its successes and failures. The role of specialist pedagogy in this process, both experiential and experimental, cannot be stressed enough. COSCH training schools, in small groups and led by inspiring teachers experienced in both theory and practice, were useful, rewarding to all involved and enjoyable, and therefore effective.

The validity of Snow's argument on two cultures was strengthened by the fact that he was both a molecular physicist and a prolific novelist. He not only spoke from an informed position, but also through personal experience of pursuing two very different disciplines alongside a high-ranking administrative career. A new generation of researchers is increasingly representative of the interdisciplinary trend, and offers a part solution to bridging the gap between discrete disciplines. A metrology scientist with a background in fine art, an astrophysicist examining historic wall paintings, an art historian applying pattern recognition to an iconographic study, or an archaeologist analysing a point cloud of an ancient structure—to use the example of some of the careers represented in COSCH—are still in the minority, but no longer an oddity. Recent research into "the perceived gap between researchers and users of research, thought to be hindering effective collaboration and limiting the impact of research" found this observation "inaccurate, with a growing group of professionals identifying themselves as spanning both roles" (Bell et al. 2014). The COSCH experience confirms these findings.

Precision is as important in communication as it is in science and technology. Training in research methods should include interdisciplinary communication and academic writing skills, to minimize unintended factual errors due to insufficient command of language. Confident use of plain and correct language empowers communication and interaction in research-making processes. When the language is incorrect and imprecise, then ambiguity or even misunderstandings are likely. Quality research risks being lost through poor communication and presentation. Much of international interdisciplinary research, of which COSCH was an example, is being conducted and disseminated in English. This disadvantages many non-native English speakers. Those fluent in colloquial English seem sometimes to underestimate the importance of highly nuanced and precise academic communication. A distortion of the intended meaning results in misunderstandings and knowledge being altered or lost in translation. For example, a common misunderstanding amongst non-native English discussants of research into cultural heritage is the misuse of the term "science," often seen as a general term encompassing all learned disciplines of knowledge. Arts and humanities disciplines are often, incorrectly, being termed "scientific"; an academic humanities scholar is sometimes, wrongly, called a scientist; human sciences are confused with the humanities, whilst arts, which encompass many creative academic disciplines, are often narrowly understood as strictly fine art practice—the examples of the wrong choices of word are plentiful not only in speech, but also in scholarly literature. When unaware of this and similar misuse, native speakers of English misunderstand the nature of intellectual argument; the communicator is unaware of the miscommunication and both parties continue the dialogue based on false assumptions. It is therefore necessary to restate the obvious: good professional language skills and high standards in academic writing are essential for ensuring effective scholarly communication.

Standards and Guidelines

Arts and humanities thrive on critical disagreements. Can scientists and engineers disagree about the best optical method of recording cultural heritage? Many guidelines and technical standards exist to facilitate the answer, but we have learned in the course of COSCH that deciding which of the many standards available is "best" depends on a number of factors and a particular research scenario. How to convey the measure of accuracy of colour registration or representation? The same goes for geometrical registration. What standards and procedures are likely to ensure the sustainability and long-term preservation of digital scholarship and its dissemination? These are key issues in the digitization of cultural heritage. The contributors to this book refer, independently, to VDI/VDE standards of the Association of German Engineers, and to ISO standards of the International Organization for Standardization. The revised image preservation technical guidelines of the Federal Agencies Digitization Guidelines Initiative (FADGI 2016) and Metamorfoze (van Dormolen 2012) were brought to the attention of COSCH by Olejnik-Krugły and Korytkowski (2017), when they presented solutions for colour-accurate archiving of images of paintings through spectrophotometry, at the COSCH final conference, held on 11 October 2016. The ISO image quality standards 19262, 19263, 19264 also concern archiving. For some researchers involved in cultural heritage, and using digital images extensively, even the basic calibration of devices used daily (computer screen and printer) are an obscure area, making them wonder, why, what they see on the screen differs in colour from a print of the same. The effort to learn the basics of colour resolution, display resolution, and print resolution may help with resolving the error (not a mystery) of bad colour representation. Art specialists, who have high visual literacy and sensitivity to perception and aesthetics of colour must not be shy in seeking advice on technical matters. The COSCH experience shows that the information will be generously provided by those in the know.

The lack of universally accepted standards, or too many standards, is an issue no research into applied science and technology can ignore. Universal standards are not in the commercial interest of the manufacturers and providers of proprietary solutions, but they are vital for the advance of science across disciplines.

The Future

According to Graff (2015, 1) the term "interdisciplinary" is so ubiquitous in today's scholarly writing that it is not unreasonable to assume that interdisciplinarity is becoming "the dominant form of scholarly work"; the critics are uncertain whether this phenomenon is positive or negative. Research described in this volume demonstrates the extent to which modern conservation and documentation of cultural heritage rely on different disciplinary components. Digital data, electronic tools, and computational methods cross-permeate academic disciplines making them potentially more contingent than ever before. The COSCH experience of interdisciplinary collaboration has been intellectually stimulating and has delivered a range of practical benefits to academic and professional advancement. Practitioners are best qualified to articulate unresolved problems and admit that applying digital technologies to the study and preservation of cultural heritage is not all clear cut. It was argued in 2005 that "Currently, 3D modeling is too expensive, too time consuming, and not suited for conservation" (Eppich and Chabbi 2006, 11). This argument referred to the then developing regions, but many heritage institutions, even in relatively prosperous countries, particularly poorly funded provincial museums find themselves in this situation. Digital research cannot be viewed solely from the perspective of rich Western establishments; these should proactively contribute to the distribution of skills and resources to disadvantaged research communities worldwide. Researchers involved in COSCH participated in such international projects and have made most of the output of their work freely accessible worldwide.

COSCH activities evidenced the support available for interdisciplinary digital scholarship and its due prominence across the European Union and beyond. COSCH researchers fully support the recommendation "that funding extends over longer periods to grow and sustain partnerships between organisations committed to promoting collaborative heritage science research" (Bell et al. 2014). Networking opportunities similar to COSCH, and face-to-face communication in particular, should be encouraged and enabled. They provide a way forward for enhanced interdisciplinary communication, but alone cannot make a real difference in advancing research. Both a vision combined with adequate resources is needed to ensure that innovators are not trapped in conservative research environments that underuse their talents. Applying for research grants has become obligatory for academic positions, but is disproportionately time-consuming relative to the rate of success. Far too few grants are chased by too many applicants.

Owing to the complexity of the field and the speed with which technology develops, many unresolved questions remain, even for well-resourced establishments in leading economies. In our era of hyper-connectivity the ease of scholarly communication is unprecedented. With benefits come risks. We are prone to the overload and chaos of information, distraction, and superficial modes of critical engagement. Our times, lives, institutions, and work patterns have been defined as "liquid."[4] Research benefits from a global reach, but its efforts continue to be fragmented. Research funding is predominantly short-term and does not prioritize continuity. This situation is counterproductive to stable research environments, but may also be seen as conductive to new developments and ideas. Digital technology benefits research, while also making its digital outputs vulnerable to

4 *Cf*. A concept in critical sociology and analysis of modernity of Zygmunt Bauman, the author of, *inter alia*, *Liquid Modernity* (2000), *Liquid Life* (2005), and *Liquid Times* (2007), all from Cambridge: Polity.

improper preservation. Novel developments tend to supersede the future technologies of the past; important evidence of past visual and other non-text-based communication risks being lost. This book records a particular research perspective and practice of the 2010s. We hope that the critical discussion of COSCH's successes and failures will be instructive to those with an interest in this interdisciplinary field and the ability to take it forward.

To conclude the two cultures argument on a lighter note, a COSCH researcher may be quoted, saying "I'm not creative, I'm a scientist!" (COSCH ESR Think Tank, 20 October 2015). Indubitably wrong, this admission may be considered in the context of the artistic theory of Josef Albers (Fesci 1968): "the creative process is the same secret in science as it is in art. They are all the same absolutely. . . . art is concerned with human behavior. And science is concerned with the behavior of metal or energy. . . . It's the same soul behind it. The same soul, you see."

Part 2

METHODS AND TECHNOLOGIES

Editorial Note

In this part of the book digital methods and technologies employed in the COSCH case studies, discussed in the preceding chapters, are explained. Entries generally follow the same structure: definition, description, exemplars, and key literature. The basic principles of each method or technology are defined for a lay reader. This is followed by a specialist technical description and examples of significant applications and key literature. The reasons why the application of a particular method/technology may be useful for recording and studying material cultural heritage are explained. This information was correct at the time of writing, October–December 2016. Additional literature can be found in Selected Bibliography.

3D DEPTH SENSING

GEORGE PAVLIDIS and SANTIAGO ROYO

Definition

Three-dimensional depth sensing can be defined as the ability or capability to tell the distances from a reference point, or observer, to all objects in a 3D scene. In technological terms, it requires a system able to take measurements, or employ computational methods, or a combination of those, to estimate distances from the system itself to all objects in its surroundings. In cultural heritage applications 3D depth sensing is at the heart of most 3D digitization systems (in some cases termed 3D optical documentation). Several restrictions apply, including the proper handling of valuable and fragile historic objects.

Description

Technically, 3D depth sensing is the process of acquiring the distances of all points in a 3D scene from a fixed point of reference, which in most cases is the sensing device itself. There are a number of different methods and technologies for sensing the depth in 3D space. Usually these methods are categorized into *light-dependent* and *light-independent*:[1] a *light-dependent* system senses light, in any way, in order to assess the three spatial dimensions, whereas *light-independent* employs methods not directly sensing light, but using geometrical and topographical principles. In addition, mainly within the category of light-dependent methods, a further sub-classification is based on the principle used or the technology being applied. These are the *active* and *passive* methods: *active* in a sense that the measuring system formulates the conditions of the measurements in order to acquire depth, whereas *passive* methods rely purely on computation applied to raw "unsupervised" measurements.

1 "Light-independent" is being used here only to emphasize a distinction among the various methods in 3D depth sensing.

Numerous methods can be found in the literature, and here is a list of the most cited in their category:

1 Light-dependent methods
   a Active methods
      i Laser triangulation
      ii Time-of-flight scanning (or LiDAR, LADAR, range scanning)
      iii Structured-light scanning
      iv Shape from Photometry
      v Shape from Shading
      vi Shape from Shadow
      vii Tomography (of any kind)
      viii Holography
   b Passive methods
      i Photogrammetry
      ii Structure from Motion
      iii Shape from Silhouette
      iv Shape from Stereo
      v Shape from Texture
      vi Shape from Focus (zooming)
      vii Microscopy (of any kind)
2 Light-independent methods
   a Topographic methods
   b Empirical methods
   c Contact sensing methods.

3D depth sensing has been the focus of intense research for a number of decades in various domains, mainly in computer vision and robotics. It has been a key point in developing autonomous systems and 3D digitization technologies. *In the context of cultural heritage 3D depth sensing can be considered as the basic process of a 3D digitization method used to capture the geometric and spectral characteristics of an object.* It has attracted serious R&D by multidisciplinary research groups in order to meet specific requirements in this domain. Since the main subjects of digitization in cultural heritage are precious objects of various sizes, such as monuments, architecture, archaeological sites, and historical urban areas, it is evident that there is a wide spectrum of challenges to be met by systems that would be capable of accurately recording the geometry and surface colour and texture in all these cases. The characteristics of the cultural heritage objects vary mainly along three axes:

1 Size and shape
2 Morphological complexity
3 Diversity in materials.

This three-dimensional space of object characteristics (fig. 11.1) results in a rather noticeable set of challenges in cultural heritage digitization projects. As the 3D depth sensing methods are adapted to specific cases, there is not a single 3D depth sensing method to fit all digitization projects. For example, as indicated in figure 11.1 the pink blob corresponds to a region in which laser triangulation methods can be successful, the green blob corresponds to a region in which range scanning methods can be used, and the cyan blob depicts a region in which Structure from Motion is expected to be successful. In order to choose the most appropriate 3D depth sensing method for a project, it is imperative to define the meaning of "successful" as stated in the previous sentence; the answer would include technical aspects (such as accuracy, resolution, precision requirements) and other managerial and usage limitations (such as the available resources including personnel, equipment, time and budget, possible restrictions in access and requirements of the end-user).

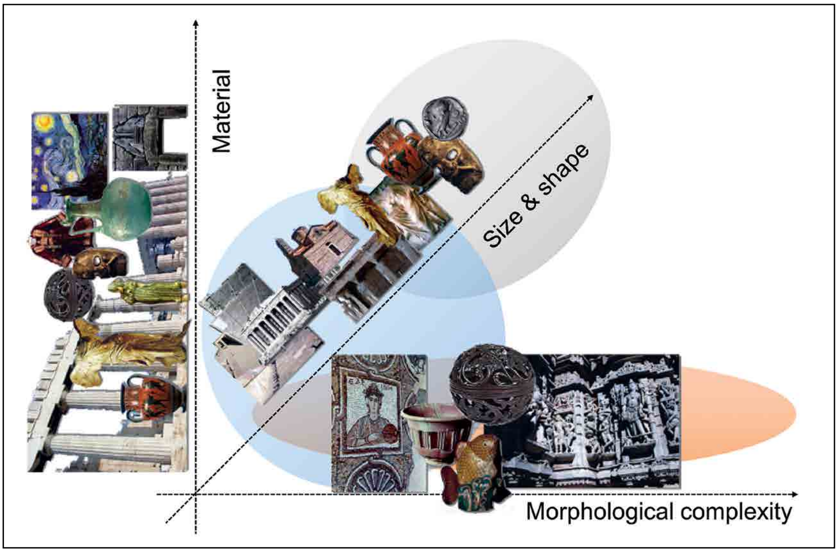

Figure 11.1. The three axes of characteristics of an object.
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With the recent significant increase in the processing power of computers, intensive computational methods, like Structure from Motion, are becoming popular because they are able to tackle large digitization projects with a relatively small amount of manual processing. In addition, solutions from the gaming industry, like the Xbox Kinect, are starting to appear in the next generation of smartphones. Products like Google's Project Tango, Intel's RealSense, and Apple's PrimeSense are bringing 3D depth sensing technology to consumer mobile devices. In these systems the basic time-of-flight principle is being used, in which the point-by-point laser beams of typical range scanners are being replaced by single light pulses. As these technologies mature and become more widely available, they will transform the traditional notions of photography, video, navigation, mapping, and gaming, and will open the way for future heritage digitization and documentation projects.

Significant Applications to Cultural Heritage

- 3D-ICONS Project Guidelines and Case Studies, http://3dicons-project.eu/eng/Guidelines-Case-Studies, 3D-ICONS Portal, http://3dicons.ceti.gr
- CARARE Project, www.carare.eu
- 3D-MURALE – 3D Measurement and Virtual Reconstruction of Ancient Lost Worlds of Europe, http://cordis.europa.eu/project/rcn/52648_en.html
- The Digital Michelangelo Project, http://graphics.stanford.edu/projects/mich/
- The CultLab3D project, www.cultlab3d.de/results.html
- Digital Heritage Toolkit, www.archaeogeomancy.net/2016/04/lidar-analysis-toolkit-for-arcgis/#more-926596

Key Texts

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3D LASER SCANNING

MONA HESS
With contribution AHMAD BAIK

The COSCH Case Studies that have employed this technology: Roman coins, Germolles, Kantharos, Bremen Cog, White Bastion, Romanian cultural heritage

Definition

Traditional surveying uses point measurements of distance and angles. 3D laser scanning does this, thousands or millions of times per second, by emitting a laser beam onto surfaces and measuring the back-scattered energy. Distance is computed from either time delay or phase-shift measurement. Alternatively, for smaller objects, close-range technologies use triangulation of a sensor and a projected pattern, for example, laser line. Therefore, the surfaces can be represented as a collection of measured points in space; as a result a digital point cloud of the surroundings is created without physically touching the surface. These non-contact optical recording technologies are therefore well suited to heritage applications as they do not disturb historic surfaces. Laser scanning is used at different scales, from small objects less than 10 cm in diameter through to heritage buildings and landscapes.

Description

All 3D laser scanners emit opto-electronic signals; the returned signals are measured. These sensors are often used in combination with a camera to include surface colour measurement. The advantage is the remote—that is, non-contact—recording of surfaces at a high speed with known accuracy. Measured surface data are digitally stored and displayed as a cloud of 3D coordinate points.

The 3D laser scanner may be regarded as the next generation of total station (see separate section), with the ability to record millions of coordinate points rather than hundreds.

Two Different Principles of Recording

Medium or Small Objects – Triangulation Laser Scanning

For small tabletop to medium-sized objects (between ca. 15 cm and 600 cm) a scanhead with a triangulation system (see examples 1 and 2) is used. For the triangulation, a laser beam is projected as a line, and its reflection is measured as distance profile by a camera array. The triangle is formed between a laser line projection, an offset optical sensor with a known baseline to the laser emitter, and object surface, and a known angle for the emitted laser line. The projection of a laser line is produced by widening a single laser beam using a cylindrical lens so that it forms a light curtain on the object's surface. The laser line can also be guided over the object by a deflection mirror. The projected laser line is deformed as a function of the distance to the object. The system measures the two-dimensional projection of the laser line on an object, using a optical sensor matrix to calculate a 2D profile. The resulting data is a scan-line-ordered 3D point cloud. The quality of the data depends on the various factors including object's surface and can be adapted by varying laser brightness and using software filtering parameters according to the object's properties. Densities of point clouds typically go down to a point spacing of 0.1 mm with an accuracy of 0.02 mm (20 microns) (VDI/VDE 2617-6.2, 2007).

Line-based laser triangulation sensors need to obtain a location for the automatic alignment of the laser lines in the lateral direction of movement. This can be achieved in multiple ways: optical tracking by a CMM (Coordinate Measurement Machine), mechanical tracking through an arm-based CMM, a moving reflection mirror, or one or more translation stages as well as a self-locating scanhead through targets on the surface of the object. A handheld scanhead guided around the object has the advantage of intuitive operation, as if the user were virtually painting a line over the object's surface from all sides. The operator guides the laser line over the surface, slowly and at a consistent distance and can often walk freely around the object.

Buildings, Landscapes, and Archaeological Sites

Terrestrial laser scanners (TLS) measure distances with known angles to a surface of an object at high speed, using a laser beam, in order to produce 3D coordinates. 3D laser scanners are standard surveying tools, and are used in heritage documentation to record larger objects, building interiors and exteriors, such as archaeological excavation.

A scanhead is typically placed on a tripod, or on the floor, in different positions around the object or space to be recorded. Discrete points are recorded all around this position by a mirror spinning vertically simultaneously with a motor rotating horizontally, with a rate of ca. 1 million points per second. Today's sensors feature an inbuilt CPU and a touchscreen for easy programming of the job, often a one-touch solution, which increasingly makes a connection to a laptop or battery unnecessary, thus providing a mobile solution for on-site use.

Time of Flight (TOF) or Phase Shift are two methodologies used. The points are measured directly in a metric scale. Like other survey equipment, a laser scanner on a tribrach can be set up over survey control points on the ground. Furthermore, geometrical targets (such as spheres or turn-targets with constant centroid from different viewpoints) are placed around the scene to help align scans at different positions (i.e., the registration of different scans into one common coordinate system). Additional measurements of an independent control network (e.g., known ground control points) measured with a total station, or additional movable targets should be included. If this is not possible, a point-cloud to point-cloud alignment can also be performed. The minimum distance to the object changes by 3D scanner model, but typical values are 1.5 m minimum standoff and 80 m–120 m reach. The sampling density can be as small as a 1 mm × 1 mm grid at a defined distance.

As well as highly accurate 3D data, the laser scanner captures a scene in colour through an inbuilt or added, calibrated camera. The set of coordinate points collected is known as a point cloud. Point cloud data are compatible with many of the CAD programs used in architecture and design. The resulting point cloud can then be used to export 2D floorplans or sections, or to digitally visualize, measure, reconstruct, and interpret the measured data set. Ongoing research explores how 3D imagery from heritage buildings can be translated into information-rich elements by parametric modelling in Building Information Modelling (BIM) systems for building management. Increasingly, research is directed towards Heritage BIM (HBIM, see example 3).

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Significant Applications

Example 1: The Digital Michelangelo Project, 1990s

The Digital Michelangelo Project at Stanford University, USA, involved recording marble statues with 3D triangulation laser scanning. It was the first 3D big data project in the 1990s and therefore ground-breaking for the 3D digitization of cultural heritage. It integrated technical solutions for 3D imaging and dissemination of the results to researchers worldwide through a dedicated website. Mark Levoy, Roberto Scopigno, and other researchers recorded Michelangelo's *David* in Florence in great detail in the late 1990s with a triangulation laser scanner (Levoy 1992). Significant technical knowledge was gained from the scanning of marble as a translucent surface (Godin et al. 2001) and the administration and visualization of large 3D data sets (Levoy et al. 2000). Information valuable for restoration was obtained from the 3D data set of the statue. A 3D data processing strategy and visualization tool for scientific investigation by cultural heritage professionals was developed (Scopigno et al. 2003). Following on from the first imaging project a new data set was recorded with structured light scanning after the restoration of the *David* statue when there were concerns about fine cracks on the surface in 2010. The research on the marble statue and its structural and surface integrity continues to this day.

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Example 2: The James Watt Virtual Bust, 2010s

This project involved the 3D triangulation laser scanning for non-contact documentation and visualization in 3D of a museum artefact (fig. 12.1). It followed a request from the curator of Mechanical Engineering at the Science Museum, London. It considered the opportunities for 3D imaging and printing in museums and the development of best practice to match the available technology to the needs of users of 3D digital and printed artefacts. This could provide a significant precedent for creating exhibitions and digital documentation for museum holdings.

Non-contact 3D imaging methods and 3D printing were used to produce a physical replica of the original "negative" plaster-cast form, dating from around 1807, which was found in the workshop of the engineer James Watt. It was paramount for the conservation of the original to use a non-contact method so as not to disturb the material and surface inside the mould. The form was complex, composed of four main pieces containing a total of twenty-nine separate sub-pieces. 3D colour laser scanning was used to record the plaster cast with a sampling grid of 0.1 mm. The digital 3D models of the components of the cast form were aligned and the surface normal directions were inverted to create a positive surface model. The result was a first image of the cast and was immediately recognized by the curator as a previously unseen portrait

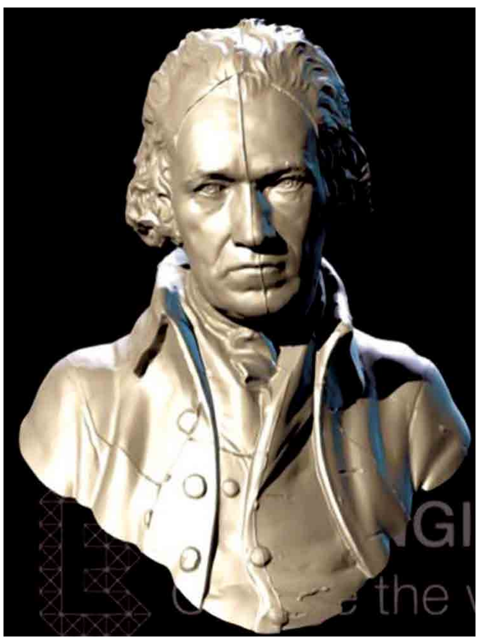

Figure 12.1. Virtual Reality display and 3D printed replica from 3D scan of a negative cast form. © Mona Hess, 2016.

of James Watt. Further processing followed the curator's decision that the model should show the manufacturing process of the casting and that the joint lines of the single cast form should remain visible and elevated. In a subsequent step the full resolution 10.5 million points was transferred into a high-resolution polygon mesh of 1.5 million polygons for 3D printing as a closed 3D surface without holes (i.e., watertight). A cutting plane was introduced to form a base and bore hole for mounting the bust. This project demonstrated the full production cycle from an original negative plaster cast to the final product in the form of a physical exhibition replica, including the 3D data acquisition to produce a high-resolution 3D virtual model, which can be regarded as the digital equivalent of a conventional plaster cast mould. The replica has been accessioned and exhibited in "James Watt and Our World" and is also available as a Virtual Reality (VR) app.

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Example 3: Jeddah Historical Building Information Modelling (JHBIM) for the Documentation of Historical Architectural and Monuments

(with kind contribution from Ahmad Baik, 3DIMPact Group, CEGE, University College London)

This project outlines a new approach for the integration of 3D Building Information Modelling (BIM) and the 3D Geographic Information System (GIS) to provide semantically rich models, and to gain the benefits from both systems to help document and analyse cultural heritage sites. Conclusions for dealing with big data in heritage documentation have also been drawn.

Jeddah is one of most important cities in the Kingdom of Saudi Arabia with numerous historic buildings over 300 years old. The major issue that faces Jeddah today is how the government can preserve and save the buildings from the risk of collapse and erosion by natural and human factors, and disasters such as fires. The municipality of Old Jeddah City decided to preserve and develop this area. The geospatial technologies applied were a combination of TLS, remote sensing, Global Position System (GPS), and architectural photogrammetry. These data

Figure 12.2. Jeddah HBIM project. © Ahmad Baik, 3DIMPact group, Civil, Environmental and Geomatic Engineering, University College London, 2015.

sources were used as input to the Jeddah Historical Building Information Modelling (JHBIM) for analysis.

The resulting data (fig. 12.2) provide a shared knowledge resource for the physical and functional characteristics of the historical building facilities in old Jeddah, and will enable decision making about the maintenance of historical structures. Furthermore, 3D models from JHBIM can enable remote reviewing of the interior and the exterior with better understanding than 2D plans and section drawings. The results will be of relevance to a wide variety of disciplines ranging from engineering, architectural and urban studies to geospatial science.

Source

Baik, A., Yaagoubi, R., Boehm, J. 2015. "Integration of Jeddah Historical BIM and 3D GIS for Documentation and Restoration of Historical Monuments." *Proc. 25th International CIPA Symposium*, Taipei, 29–34. International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences XL-5/W7. ISPRS.

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AUGMENTED REALITY

JEAN-PHILIPPE FARRUGIA and FRÉDÉRIC MERIENNE

COSCH Case Study that has employed this technology: Germolles

Definition

Augmented Reality (AR) is a group of imaging techniques designed to blend virtual and real elements in a coherent scene. Usually, an Augmented Reality application allows a user to navigate in a real environment with an augmented visualization of synthetic elements. This technology has numerous applications, from digital entertainment and video games to specialized professional training and simulation. At the time of writing, AR applications are mainly implemented on smartphones or tablets, which offer an ideal combination of hardware (sensors, cameras, graphics processor, and powerful processing units) for this task.

Description

From a practical point of view, augmenting reality means synchronizing and fusing heterogeneous representations of both actual and virtual scenes. Depending on the targeted application, this fusion needs to be precise and/or complete. For instance, specific applications may require the virtual elements to be positioned very precisely. Other applications may need to be visually convincing, with realistic shading, occlusion, and shadows.

Augmented Reality covers many different software and hardware technologies and is therefore difficult. Its challenges may be presented through three important principles: co-localization, co-occlusion, and co-lighting.

Co-localization means aligning the real scene with the virtual scene: the camera of the virtual scene is placed at the same coordinate location as the physical camera (fig. 13.1). This process is generally achieved through a combination of computer vision techniques with specialized sensors: accelerometers, GPS, gyroscopes, depth cameras, etc. It may also be facilitated by placing custom markers

Figure 13.1. Augmented Reality with co-localization and co-lighting (no co-occlusion). © Jean-Philippe Farrugia and Frédéric Merienne, 2015.

Figure 13.2. Augmented Reality with co-localization, co-occlusion, and co-lighting. © Jean-Philippe Farrugia and Frédéric Merienne, 2015.

throughout the environment. These markers look like two-dimensional barcodes and present high contrast to enable easy detection. By comparing their projection onto the camera image plane with a reference picture, it is possible through basic linear algebra to retrieve the position of the user. Marker-based co-localization is usually more robust than marker-less and sensor-based techniques, but it is also more intrusive.

Co-occlusion means taking into account the geometry of the real world when rendering virtual elements. Specifically, virtual and real elements should occlude each other, depending on their respective shapes and locations in the environment. Since the shapes of the virtual elements are known, the significant challenge is to acquire the geometry of the real elements. This is generally done with dedicated scanners or depth cameras, offline (in advance, ahead of usage) or in real time if the device has the necessary hardware.

Co-lighting means computing light interactions between real and synthetic elements. For instance, a virtual object lying on a real desk should project a shadow onto the desk. Similarly, synthetic objects should be illuminated or shaded by the real lights of the environment. Achieving co-lighting is difficult since it requires two simultaneous tasks: dynamically capturing ambient lighting and rendering virtual objects with this potentially highly complex data. To date, only *ad hoc* real-time solutions provide a viable way of meeting this challenge.

Significant Applications

Augmented Reality has been used for several purposes in the cultural heritage domain: for archaeologists, as an assessment tool; for tourists, for a better understanding of a site; and for museum stakeholders, for planning and education (fig. 13.3). Early projects in the 1990s explored the added value of AR for cultural heritage. Some of them, funded by the European Union, were focused on European archaeological sites. For instance, in the Archeoguide project (Vlahakis et al. 2002) a mobile AR system was developed. The project focused on issues of localization (tracking), mobility (portable system), and narration (using an avatar in a virtual scene). The system provided onsite help and AR reconstructions of ancient ruins, based on the user's position and orientation within the cultural site, as well as real-time image rendering. It incorporated a multimedia database of cultural material for online access to cultural data, virtual visits, and restoration information.

As a proof of concept, an application was developed for the ancient archaeological site at Olympia in Athens, Greece. The Gunzo project (Durand et al. 2014), funded by the European Regional Development Fund and the authorities of Burgundy, France, developed an on-site AR system, allowing virtual re-creation of the Cluny III abbey (1088–1109) demolished in the early nineteenth century. Using on-site visualization devices, visitors may switch between a view of the present architectural remains of the monument, and the view into the medieval abbey church's nave or choir, recreated with consistent materials and lighting. Because a real-time computation of lighting was not possible, the device was placed in a specific area and the rendering was carried out offline.

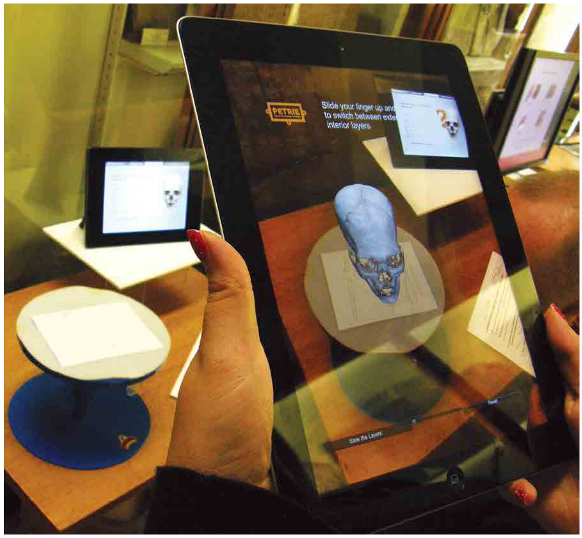

Figure 13.3. Studying a museum object through AR. The UK V-Must School at the University College London Petrie Museum. Photo: Martin Blazeby, 2013. Reproduced by permission.

More recently and thanks to the fast development of smart mobile devices, many companies, including Humarker, Marte5, and Paztec, have emerged. New applications for cultural heritage, such as LecceAR, have been developed.

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DIGITAL STORYTELLING

SELMA RIZVIĆ

COSCH Case Study that has employed this method: White Bastion

From early mankind people have communicated through storytelling. Throughout history the concept has remained the same, but the tools and methods have changed with time. People started writing down their stories, recording at first the sound of their voices, and finally recording audio and video clips, nowadays called movies. Digital technologies enhanced the ways of presenting stories and digital storytelling was born.

Digital storytelling is narrative entertainment that reaches the audience via digital technology and media. Handler Miller (2008) states that digital storytelling techniques can make a dry or difficult subject more alive and engaging to the viewers. In order to enhance the classic storytelling concept, in which the listener remains passive, Glassner (2004, 8) defined interactive storytelling as a two-way experience, where "the audience member actually affects the story itself." Manovich (2002, 218) also considered the possibility for the audience to change the story and offered the concept of an interactive narrative as "a sum of multiple trajectories through a database."

One of the most common concepts of hyperlinked story structures is the hypervideo, first demonstrated by the Interactive Cinema Group at the MIT Media Lab. *Elastic Charles* (Brøndmo and Davenport 1990) was a hypermedia journal developed between 1988 and 1989, in which *micons* (video footnotes) were placed inside a video, indicating links to other content. Following the Storyspace project, a hypertext writing environment, the HyperCafe, an award-winning interactive film, placed the viewer inside a virtual cafe. It is a video environment where stories unfold around the viewer (Sawhney et al. 1996). After these first works, and a rather long period of stagnation, many different methods of hypervideo implementations started to appear with development of the Internet, starting in 2010, most of them for use in advertising and marketing. Nowadays there are several popular tools using hypervideo. In the RaptMedia cloud-based editor (www.raptmedia.com) the user can create interactive videos and controls implemented in the form of links on the web. The Madvideo tool (www.themadvideo.com) is used to add tags to video files. Interactivity is implemented via manually inserted interactive tags. The tags can be links to websites, images, or other video clips. In the Open Hypervideo project (Jäger 2012) the content is linked using annotation-types, such as Wikipedia articles, locations, videos, and web pages. Video sequences are made out of multiple (cut) video files. In E-Learning-How-Tos (http://learn.articulate.com) the learning process via videos is enhanced using elective contextual data inside the videos. Cacophony, the interactive player for HTML 5 and JavaScript (www.cacophonyjs.com/) allows the creation of interactive elements inside videos, such as the story adapting in response to the user input. ClickVID video players (www.clickvid.co.uk) allow the creation of "hotspots," clickable regions with specific content at designated times. WebM is a video file format made for HTML5 video tagging.

Apart from these fields of application, hyperlinked storytelling is also used in virtual cultural heritage applications. A Human Sanctuary is a project implemented in 2013 by the Cyprus Institute, telling the story of the famous Dead Sea Scrolls; text annotations offer more details about certain notions mentioned in the video (http://public.cyi.ac.cy/scrollsDemo). In the Keys to Rome exhibition (Pescarin et al. 2014) the interactive digital storytelling was used to present the reconstructed Roman remains from Rome, Amsterdam, Alexandria, and Sarajevo in combination with physical museum exhibits.

New approaches to digital storytelling increasingly emphasise the role of emotive personalized storytelling (EMOTIVE H2020 Project 2016–19). Technically, branching stories may be implemented within a common hyperstructure placed within interactive virtual environments (Rizvić and Prazina 2015). There is still no method which would satisfy all user categories, from gamers to people without much computer experience. Therefore it remains a hot topic in multimedia communications research.

Key Texts and Resources

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FOCUS STACKING

AURORE MATHYS and JONATHAN BRECKO

The COSCH Case Study that has employed this technology: Roman coins (fig. 15.1)

Definition

Focus stacking is a technique which extends the depth of focus of an image by combining different images with low depth of field. It is mostly used in close-up and macrophotography since in those cases the lens, even at high f-stop, is not able to render everything in focus. This method, although not used often in cultural heritage, is useful to document objects and to illustrate details. It can also be used in combination with Structure from Motion (SfM) in order to create accurate 3D models of small artefacts.

Description

Focus stacking allows the extension of the focus range of a single view, using the lens at its optimal f-number (typically in the range f/8 to f/11). If the lens is stopped down more than its optimal f-number, the depth of field is larger, but the image is softer (less sharp) due to diffraction. The starting point for focus stacking is a series of images, with different regions in focus. Although none of the images has the object of interest entirely in focus, collectively they contain all of the data required to generate an image that has all parts in focus. The in-focus regions of each image may be selected manually or detected automatically, for example, via edge detection or a sharpness metric or Fourier analysis. The in-focus regions are then blended together, pixel by pixel, to generate the final image.

This process is also known as z-stacking or focal plane merging.

Figure 15.1. Focus stacking record of a Roman coin. © Aurore Mathys, 2015.

Significant Applications

Example 1: Rock Art Studies

Plisson and Zotkina (2015) tested the potential of focus stacking for 3D recording of submillimetric details of prehistoric petroglyphs and paintings. They tested their technique at open air sites in France, Portugal, and Russia. The study shows that focus stacking and photogrammetry are complementary.

Plisson, H., Zotkina, L. V. 2015. "From 2D to 3D at Macro-and Microscopic Scale in Rock Art Studies." *Digital Applications in Archaeology and Cultural Heritage* 2.2: 102–19.

Example 2: Venus of Frasassi

The Venus of Frasassi is an 87 mm high Palaeolithic sculpture carved in a stalactite. It was found in a cave in the Frasassi Gorge (hence the name) in Central Italy and is housed in the National Archaeological Museum of the Marche in Ancona. The figurine was recorded using focus stacking pictures combined with photogrammetry to achieve a 3D model. The model was compared to 3D data captured through a state-of-the-art laser scanner, and the results were shown to be similar, at a lower price. Therefore focus stacking combined with photogrammetry has potential for the 3D digitization of small artefacts.

Clini, P., Frapiccini, N., Mengoni, M., Nespeca, R., Ruggeri, L. 2016. "SfM Technique and Focus Stacking for Digital Documentation of Archaeological Artefacts." *Proc. 23rd ISPRS Congress*, Prague*, 229–36.* International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences XLI-B5. ISPRS.

Figure 15.2. Edge of an ancient copper nail. The nail was broken and restored, but broke again after some time. The glue used to fix the nail is clearly visible. © Jonathan Brecko, 2015.

Literature

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HYPERSPECTRAL IMAGING

ANDRÁS JUNG

COSCH Case Study that has employed this technology: Round Robin Test (chapter 8)

Definition

Hyperspectral imaging is the acquisition and processing of images of an object or scene in a hundred or more wavelength bands, typically spanning the visible and near infrared spectrum. The fine spectral resolution enables the identification of features and characterization of materials that would not be possible with systems which have fewer channels of broader responsivity.

Description

Hyperspectral imaging techniques are used in many scientific and industrial applications, both indoor and outdoor. Hyperspectral line-scanners have some limitations when the subject is moving or rapid measurement is needed or long-time illumination is not appropriate. To overcome these limitations a novel technique with increased light efficiency was developed with a non-scanning principle, which is called snapshot hyperspectral imaging or spectral frame camera technique. It enables the acquisition of the entire hyperspectral image during a single integration time (one shot takes about 1 ms). The latest snapshot hyperspectral imaging devices provide a rapid, high-quality and easy-to-use data acquisition for spectral object documentation.

Diffuse reflectance spectroscopy in the visible (VIS) and near-infrared (NIR) regions has been widely used in both the laboratory and *in situ* spectral measurement. Non-imaging spectroradiometers provide the highest available spectral resolution and therefore high information content for estimating material properties with multivariate methods. However, only measurements integrated over a single sampling region, determined by the aperture of the instrument, can be performed, which makes it difficult to analyse spatial variability. In contrast, a

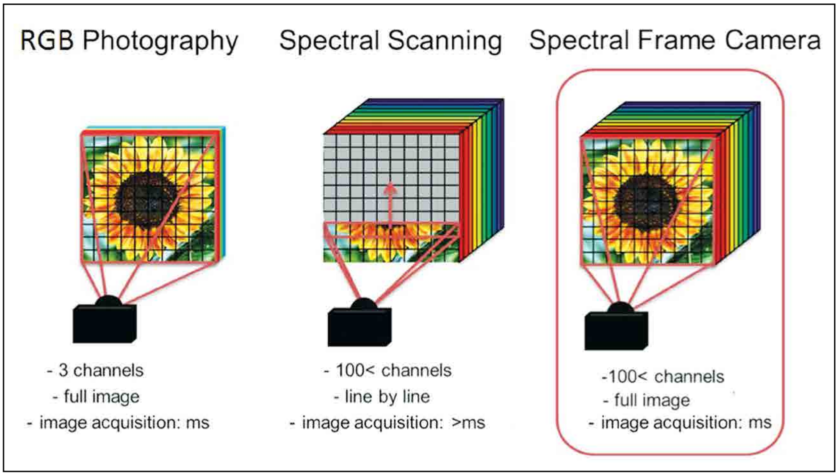

Figure 16.1. Comparison of three imaging approaches. Conventional RBG photography, spectral line-scan, spectral frame (snapshot) capture. Image © Cubert GmbH, Germany, reproduced by permission.

spectral imaging system captures both the spatial variability and spectral content at each point of the scene.

Hyperspectral imaging has undergone considerable changes regarding data access, usability, and technology. When looking at the four dimensions (spectral, radiometric, temporal, and spatial) of proximal and remote sensing, the temporal resolution is in greatest need of improvement. Regarding usability and flexibility a snapshot (non-scanning) hyperspectral camera behaves like a normal digital camera, while the imaging result is a stack of component images corresponding to the line-scanner's data cube. Hagen et al. (2012) gives a detailed overview on how snapshot systems work and have been developed. Figure 16.1 shows the main differences and similarities between the three types of spectral imaging systems. Snapshot spectral cameras provide high-resolution spectro-temporal data and meet the general demand for high quality and easy to access hyperspectral data.

A snapshot spectral camera is generally designed to benefit from real-time data acquisition. In practice, a silicon CCD sensor with a resolution of 970 × 970 pixels captures the full frame images with a typical dynamic image resolution of 14 bits. In a normal sunlight situation, the integration time of taking one data cube, with more than 100 spectral channels, is about 1 ms. Such cameras can capture more than fifteen spectral data cubes per second, which enables hyperspectral video recording.

Significant Applications

The COSCH Action initiated a Round-Robin-Test (RRT) in 2013, coordinated by the Spectral Object Documentation working group (http://cosch.info/wg1). The aim of the RRT was to compare colour and spectroscopic measurements, by imaging the same four test objects in all participating laboratories. Information on calibration standards and laboratory setups was obtained for the diverse imaging devices. It was the first time that a snapshot hyperspectral camera was involved in a cultural heritage project (Picollo et al. 2016). Jung et al. (2015) used a snapshot hyperspectral camera to detect and analyse soil constituents under laboratory and field conditions to test predictive quantitative models. Whitley (2015) reviewed technological standards and availability for archaeological applications. He emphasized the spectral advantages of snapshot systems compared to traditional cameras.

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LASER-INDUCED BREAKDOWN SPECTROSCOPY (LIBS)

VINCENT DETALLE
With contributions from DOMINIQUE MARTOS-LEVIF, BARBARA TRICHEREAU, DIDIER BRISSAUD, STEPHANIE DUCHÊNE, and XUESHI BAI

COSCH Case Study that has employed this technology: Germolles

Definition

Laser-induced breakdown spectroscopy (LIBS) is a type of atomic emission spectroscopy which uses a high-energy laser pulse as the excitation source. The laser focuses on the sample, which atomizes, excites, and ionizes the material inducing the creation of plasma. The light emitted by the plasma is analysed through a spectrometer. The emission lines are characteristic of each type of atom present in the plasma that enable an elemental identification to be made. In principle, LIBS can analyse any type of matter regardless of its physical state, be it solid, liquid, or gas.

Description

Although LIBS is better known for its industrial applications, this analytical technique can be successfully used for cultural heritage characterization. Many publications have been devoted to the identification of pigments and stones, or archaeological metal characterization (Anglos and Detalle 2014). The conservation of wall paintings is a significant part of our activities at the Laboratoire de Recherche des Monuments Historiques (LRMH) laboratory, which is part of the French Ministry of Culture and Communication. The research has two main directions: the study and identification of materials, including the development of new investigation techniques, and the diagnosis for conservation and restoration.

Dealing with this kind of heritage, we often face very heterogeneous and large surfaces (up to several hundred square metres). Their study requires a corresponding number of samples to be removed from the wall and then analysed in laboratory via “traditional” techniques such as optical microscopy and scanning electron microscopy, coupled with energy dispersive spectroscopy, infrared spectroscopy, or X-ray diffraction. Therefore, the acquisition of knowledge about the

Figure 17.1. LIBS in operation at Chartres Cathedral (left) and Château de Germolles in Burgundy (right). © LRMH, 2011 and 2015.

materials is hampered by lengthy analytical processes in the laboratory. In order to reduce the need for sampling by the selection of relevant areas, and to obtain topographical information about the distribution of materials on the surface, and also to improve the direct understanding of materials, the LRMH has developed over the past ten years a portable instrument for laser-induced breakdown spectroscopy (LIBS) for elemental investigations. In fact most of the materials found in wall paintings are metal oxides or salts, so LIBS appears to be a suitable technique for the identification of both pigments and the products of degradation. Indeed LIBS is characterized by high sensitivity and selectivity and can be performed *in situ*.

The LIBS approach offers new possibilities as it requires neither removal nor preparation of samples and can supply a conservator's particular requests with quick answers, relevant enough to make decisions on condition and treatment. Furthermore, as only a small amount of the sample is consumed in the process of atomization (less than 100 pg depending on the laser energy), this technique is micro-destructive. It is therefore possible to have in-depth access to layers, while other analytical techniques are restricted to the surface. Hence LIBS can reveal stratigraphic information about the multi-layered structures of wall paintings, for example.

LIBS Principle and Portable Setup

LIBS relies on the analysis of a plasma induced by focusing a pulsed laser beam on the surface of a sample. The characteristic light emitted by the excited elements contained in the sample when they settle back to equilibrium is collected via optical fibres and sent to spectrometers. Spectral analysis enables elemental identification and quantification. The portable instrumentation is composed of a 1064 nm Nd-YAG laser, with a 5 ns pulsing time and a maximum energy of 50 mJ/pulse; with a detection system located behind a lens of focal length 100 mm and based on a seven-fibre optical bundle connected to three integrated spectrometers, which cover the range 200–940 nm. The emission spectrum is recorded with an internal 2048 CCD line array detector. The optical fibres are coupled with alignment lights to control the focal spot, placed at a distance of 130 mm from the convergent lens. The laser is controlled by the spectrometer software and pulses are triggered manually, in single shots or in series. The enclosure of the lenses in a rigid case, mounted on a camera tripod with wheels, makes on-site use possible. Figure 17.1 shows the portable system developed by the LRMH in use at two different sites: first on scaffolding in Chartres Cathedral to characterize the thirteenth-century wall painting discovered in 2010; and second during a study of the painting of the Château de Germolles in Burgundy.

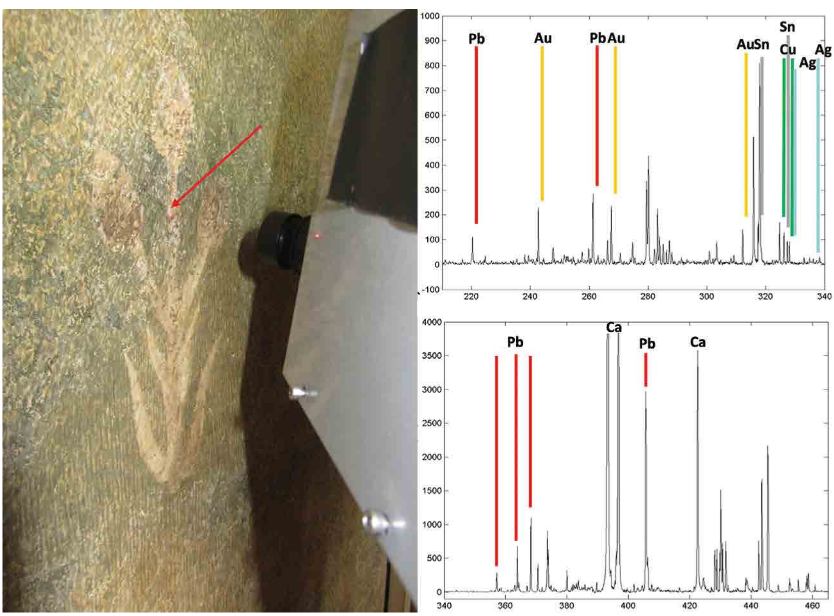

Figure 17.2. Château de Germolles, wardrobe of the Countess of Nevers, north wall, measurement localization and LIBS spectra of the third measurement. © LRMH, 2015.

The LIBS system has been applied *in situ* for many studies of mural paintings and polychromy. For example at the cathedrals of Paris, Strasbourg, Poitiers, Chartres, the papal palace of Avignon (Saint Martial Chapel), and more recently in the Château de Germolles.

The great advantage of the technique is its capability to penetrate inside the material and hence to determine the stratigraphy. Figure 17.2 shows the identification of the painting technique. This measurement is located at the transition of different layers. The top layer is made of gold (Au), then a tin (Sn) foil layer, while copper (Cu) and lead (Pb) were identified on the green background layers. LIBS confirmed these results on many other thistle motifs. The results also indicated that the gold is alloyed with silver.

In conclusion, LIBS as an analytical technique is now well established for *in situ* characterization of material. It is a very good addition to more "classical" analytical techniques such as X-ray fluorescence or diffraction. Its advantages have been demonstrated and its ability to be coupled with other laser techniques, such as Raman spectroscopy and laser fluorescence, will ensure its key role in the future of cultural heritage study.

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MULTIPLE VIEW STEREOVISION

CHRISTOS STENTOUMIS

COSCH Case Study that has applied this technology: Kantharos

Definition

Multiple view, or multi-view stereo vision is the process of reconstructing the 3D model of an object, or scene, from a set of digital images. This 3D model may be generated in several kinds of representation, for example, as a point cloud, as a photo-textured surface, or even as an orthophotograph.

Description

Stereo vision is necessary in the 3D recording of cultural heritage, as it provides accuracy, completeness, and visual quality, as well as cost effectiveness. Thus it plays an important role in the documentation, restoration, preservation, and promotion of cultural heritage assets. Multi-view vision applications may range from small artefacts to large geographic regions by exploiting any kind of optical camera (e.g., SLR, compact, mobile phone) and supporting system (e.g., trolleys, cars, UAVs, robots). Currently, many commercial software and open source algorithms exist for multiple view stereovision; some of these are more generic, others are more application specific. Although such software implementations have brought the 3D product to the public, for more demanding applications the expertise of a professional is still required.

The term multiple view stereovision refers to the automatic reconstruction of a 3D object, or scene (i.e., estimation of 3D coordinates) from more than two source images. Strictly speaking, it could be viewed as essentially an ill-posed 2D-to-3D problem, meaning that the solution is not trivial. This process may involve an arbitrary number of images with different characteristics (positions, rotations, internal camera parameters) from different cameras (still or video frames). The scenes are assumed to be static, thus moving objects are treated as outliers; a different class of methods has been evolved to treat moving and deformable objects.

Model reconstruction from multiple views consists of two main steps: sparse reconstruction and dense reconstruction, while in some cases it can also involve a texture-mapping step. Typically, the process begins with the extraction of interest points, but line or area features may also be exploited. For extracted image points, appropriate characteristic descriptors are calculated, and the point correspondences among images are established via some similarity measure. The retrieved correspondences are used in the bundle adjustment procedure, to restore simultaneously the image orientations (i.e., position and rotations). The Structure from Motion (SfM) process can also provide the camera calibration in multi-view stereo vision.

According to Seitz et al. (2006, 519), "The goal of multi-view stereo is to reconstruct a complete 3D object model from a collection of images taken from known camera viewpoints." Once the full calibration/orientation of each image has been determined, a process of dense image matching estimates all the pixel correspondences with respect to either a putative base image or a world model. A typical taxonomy of multi-view stereo vision algorithms is based on the following dominant criteria: scene representation, photo-consistency measure, visibility model, shape prior, reconstruction algorithm, and initialization requirements (Seitz et al. 2006).

The geometry of an object, or a whole scene, can generally be represented in 3D space via voxels, level-sets, or polygon meshes, which may directly handle issues of visibility and occlusion, and in image projective space via multiple depth maps. The most common photo-consistency measures are the sum of squared intensity differences, which supposes Lambertian surfaces, and cross-correlation, which supposes linear brightness changes. Other more efficient but also more complex matching functions include mutual information, which can handle radiometric differences more effectively, and non-parametric image transformation, which can produce more robust results.

Visibility models are important in multi-view stereo to define which points in the scene are visible and which are occluded in each image. For this purpose, the geometric or photometric attributes of a current 3D reconstructed model and the source images are exploited, thus requiring a two-step process. Moreover, most methods imply, or explicitly exploit, a shape prior regarding the surface of the model. In its simplest form this shape prior is the "fronto-parallel" assumption widely adopted in single stereo-matching methods. The most important classification criterion is the reconstruction algorithm, as this is the field where most advances now occur. Two general categories are global optimization algorithms, such as graph-cuts, level-sets, and PDEs, and algorithms that estimate independent depth maps then fuse them in a full 3D model. Matching algorithms for independent stereo-pairs can also be distinguished as local and global, while between them a group of semi-global and non-local algorithms has also been developed. Finally, the initialization requirements vary among methods, with the most obvious being the need, or not, of an initial model surface. A multi-view stereovision process can provide several final products, such as photorealistic 3D models, novel viewpoints, and photo-textured mappings, that is, ortho-projections.

The field of multiple view stereovision is rapidly changing as researchers in this area are very active. For a continuously updated list of state-of-the-art algorithms and their performance on dedicated data sets, see one of the various online evaluation platforms, such as http://vision.middlebury.edu/mview/, provided by the Middlebury College, Vermont, USA; The KITTI Vision Benchmark Suite, www.cvlibs.net/datasets/kitti/ of Karlsrue Institute of Technology; and http://cvlab-www.epfl.ch/data/multiview/denseMVS.html by the Computer Vision Laboratory (CVLAB) of the Ecole Polytéchnique Fédérale de Lausanne (EPFL) and part of Strecha et al. (2008).

Significant Applications

Sagalassos

One of the pioneering applications of multi-view stereovision in cultural heritage was the recording of the Sagalassos Hellenic-Roman city in ancient Pisidia (Pollefeys 2002). In this early example of applying computer vision techniques to automatically retrieve the 3D model of a landscape, the accuracy and resolution was far from the standards achieved through photogrammetric techniques, but the process was fully automated. It was possible to retrieve a complete 3D model from images for recording the excavation, the restoration process, or another purpose. Today models are created automatically from mview reconstruction algorithms and software, but the accuracy is not as good as needed, so a human has to correct the model.

Eetioneia Gate

The image-based 3D reconstruction of the East Tower of the Eetioneia Gate is an example of applying multi-view stereo vision algorithms to the recording of cultural heritage. The archaeological site of Eetioneia Gate presents a significant part of the ancient fortification of the Piraeus port of Athens since the fifth century BC. In 2015, the East Tower was recorded in a complete, high-fidelity 3D model, as a part of extensive restoration and conservation activities over the past decade. The tower was captured by 900 images via a 18 MP camera and 17 mm lens from 5 m distance; these resulted in a sub-mm resolution and accuracy of a model without occlusions. Small targets were used to verify the accuracy of the reconstruction. The orientations of the images were solved via SfM and the surface was reconstructed via custom and commercial multi-view stereo vision algorithms. The products of the contact-less recording, which were useful to architects, archaeologists, and curators, were a 3D unwrapped surface, orthoprojections viewed from several viewpoints, and the complete 3D photo-textured model. A fly-though video of the model created by up2metric, Athens (www.up2metric.com), is available at https://youtu.be/_w6RA6Xmra0 (accessed 13 February 2017).

Portus Port

The 3D recording of cultural heritage objects has also been studied and evaluated on several artefacts in the Portus Project (2007–11) and the Portus in the Roman Mediterranean Project (2011–14) (www.portusproject.org/). Led by the University of Southampton with support from the Soprintendenza Speciale per i Beni Archeologici di Roma and other academic partners, the project aimed at the better understanding of the archaeological site of a large artificial ancient harbour south of Rome. An interdisciplinary approach was adopted, involving the development of new techniques in all relevant fields: the data capturing, processing, analysis, and presentation of the results. In this scheme, several complementary recording techniques were evaluated in the context of cultural heritage monuments. Different means of recording were used, including UAVs, photographs, terrestrial laser scanners, and thermal images.

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PHOTOGRAMMETRY

JULIEN GUERY, MONA HESS, and AURORE MATHYS

COSCH Case Studies that have employed this technology: Kantharos, Roman coins (fig. 19.1), Bremen Cog (fig. 19.2), Germolles (fig. 19.3), White Bastion, Romanian cultural heritage

Definition

Photogrammetry is a metric imaging method that enables digital reconstruction of the form and geometry of a real object in three dimensions. This reconstruction is based on a set of photographic images covering all areas of the surface with enough overlap to enable identification of common details on each photo. Photogrammetry was originally developed around 1860, and can be regarded as the first non-contact measurement method.

Description

Through photogrammetry, a realistic 3D model based on simple photos including detailed and accurate colour recording of the object's surface can be achieved. It is a very good tool for recording cultural heritage objects, of any size and any type. With commercially available cameras, together with recent software developments, photogrammetry has opened up to many end-users.

The data sets are useful at different levels: on-the-ground and on-site recording (e.g., during an archaeological excavation), technical analysis (surfaces and volumetric measurement after post-processing), and public dissemination through dynamic and easy-to-manipulate 3D models.

Digital close-range photogrammetry is a robust and established, non-contact method for the documentation of museum artefacts. The equipment, typically consisting of a digital SLR camera and lighting equipment, scale bars, and a colour target, is easily transportable to museums or other sites. It is capable of recording the current condition and damages on the surface of an artefact offering visualization of details of the order of 50 microns.

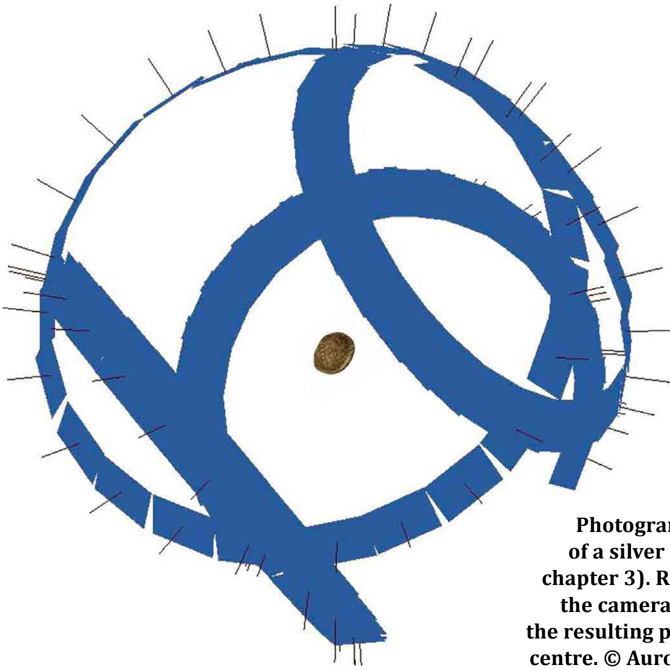
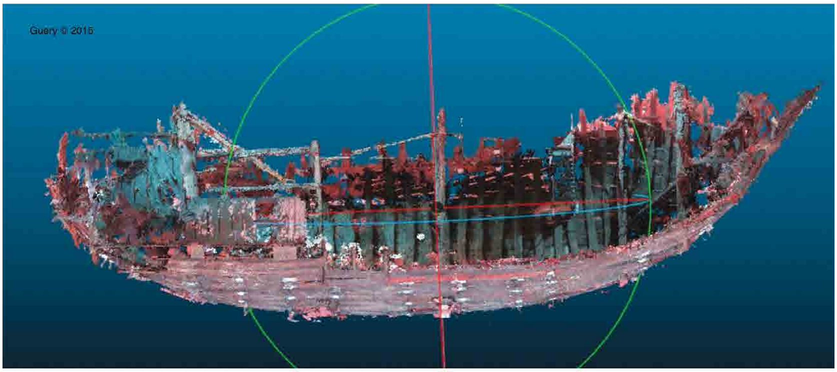


Figure 19.1. Photogrammetric capture of a silver Roman coin (see chapter 3). Representation of the cameras' positions with the resulting point cloud in the centre. © Aurore Mathys 2016.

Two or more overlapping images are taken from different locations. Measurements of a distribution of common imaged features, usually discrete points, are recorded from which both the image and surface geometry can be solved. If many overlapping images, often termed an "image network," are taken, it is possible to estimate both the pose and interior optical parameters of the camera and to produce accurate 3D surface measurements with consumer-grade digital cameras. This procedure, termed "self-calibrating bundle adjustment," is fundamental to many automated 3D image reconstruction procedures when it is combined with automated image feature and area matching processes. Given that colour images are taken, it is a relatively straightforward process to map the colour in the images onto the 3D surface. However, one key point concerning the use of photogrammetry is that the scale of the developed model is unclear unless a scale bar or a known separation between a camera pair is included (MacDonald et al. 2012). The final 3D model can be output as point cloud or TIN (triangulated irregular network) in various formats.

The restitution of the surface relief through photogrammetry is based on the principles of stereoscopy (like human vision), where each pair of photos represents the same details from a different viewpoint (Kraus and Waldhäusl, 1998). Algorithmic analyses of these photo pairs makes it possible to identify each detail



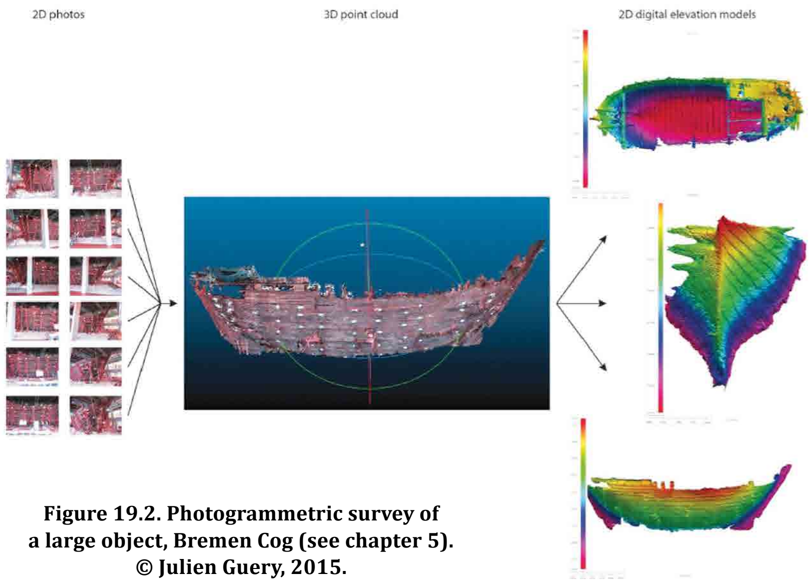


Figure 19.2. Photogrammetric survey of a large object, Bremen Cog (see chapter 5). © Julien Guery, 2015.

as common points, which are then used to determine the relative position of each photo in relation to the others (this operation is called aerotriangulation; Pierrot-Desseiligny and Clery 2011). It is then possible to triangulate the position of specific points recognizable on at least three photos, according to the principles of epipolar geometry (this is referred to as dense epipolar correlation; Zeroual et al. 2011). The procedure can be repeated until several million points have been generated, forming a point cloud comparable to that obtained by a laser scanner, with the difference that each point generated by photogrammetry, besides XYZ information, has colorimetric information derived from the corresponding pixels in the images (Hullo 2010).

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Significant Applications

Example 1: Rescue Photogrammetry: Reconstruction of the Great Buddha Statue in Bamiyan

The two statues of the Great Buddha in the Bamiyan Valley, Afghanistan, which were created in the fourth and fifth centuries, were destroyed in March 2001 by the Taliban. A virtual reconstruction in 3D of the larger 53 m high figure, using photogrammetry was carried out by a team from ETH Zurich. Researchers used amateur photographs taken from the Internet and scanned photographic prints from the 1970s. This was a significant application because it enabled reconstruction of lost heritage, using pictures that were not made for scientific purposes. Since then many similar photogrammetric reconstructions were undertaken using the same principles, in particular for the sites destroyed in Syria during the Civil War since 2011.

Figure 19.3. Photogrammetric survey of architecture, the Château de Germolles (see chapter 4). © Julien Guery, 2015.

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Example 2: Underwater Photogrammetry: The Phanagorian Shipwreck

In 2012, a wooden ship was discovered on the Taman Peninsula at the ancient Greek settlement Phanagoria (Zhukovsky 2013). Photogrammetry was used *in situ* to acquire the 3D model. Underwater photogrammetry works in a similar way to terrestrial photogrammetry, but presents a few extra challenges such as the refraction of water, the presence of the camera housing, low visibility, and turbulence of the water. Underwater photogrammetry can be done by a diver or by using an underwater remotely operated vehicle (ROV).

Extracting wood remains from water is an extremely delicate process since the wood has a tendency to disintegrate once in contact with air. Storms can affect or destroy at any time the unearthed artefacts. Hence the excavation and field documentation recording need to be conducted in a very limited time span. In this case photogrammetry proved to be an efficient recording technique. Furthermore underwater sites can rarely be experienced first hand by archaeologists and the general public. It is therefore crucial to generate a faithful 3D reconstruction of the site, which can provide virtual access to all archaeological data (Drap 2012).

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Example 3: Dimensional Monitoring for Conservation of Artefacts by Photogrammetry

Digital documentation supporting the conservation intervention of museum objects can be enabled by photogrammetry. An example is the detailed documentation of the medieval Westminster Retable made for Westminster Abbey, London, a fine example of late thirteenth-century panel painting. A multi-image photogrammetric system was used to carry out periodic, non-contact, detailed motion analysis of mechanical deformations (dimensional monitoring) in response to environmental changes. The image record and associated spatial data were then used as a visual database used to manage the conservation process and automatically generate a 3D surface model which allowed the art conservator to make measurements and comparisons between different parts of the structure (Robson et al. 2004). This methodology can also be applied to dimensional monitoring of other contexts in cultural heritage, such as building façades and rock faces with rock art, provided that stable surface features are present and/or an independent system of reference points is installed.

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REFLECTANCE TRANSFORMATION IMAGING

LINDSAY MACDONALD

COSCH Case Studies that have employed this technology: Roman coins, Germolles (H-RTI)

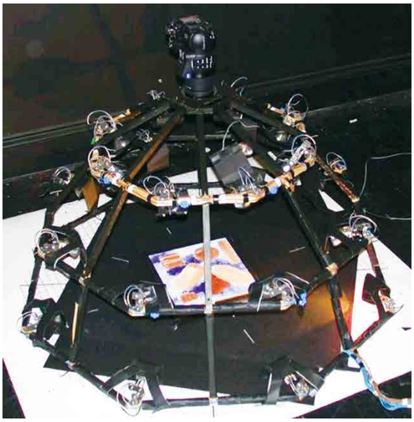
Definition

Reflectance Transformation Imaging (RTI) is a family of methods for modelling the distribution of light reflected from an object surface as functions of space, angle, spectrum, and time. One instance is the Polynomial Texture Mapping (PTM) technique, which enables the visualization of relief surfaces under a variable lighting direction.

Description

Malzbender et al. (2001) introduced PTM as a novel image-based relighting technique, which takes a set of digital images of an object, all captured from a fixed camera position, each lit by a point source at a different but known coordinate position. Malzbender designed and built the original apparatus at HP Labs, Palo Alto, California, from an acrylic hemisphere of diameter 18 inches (45 cm) with twenty-four flash lights. He demonstrated the power of the PTM technique for the visual representation of objects with surface relief, such as fossils and inscribed clay tablets.

The PTM algorithm fits a biquadratic function (two-dimensional parabola with six parameters) to the set of intensities at each pixel location. The interactive viewer software then uses the cursor position, representing the geometric coordinates of a virtual light source, to generate the intensity of each pixel as if it had been illuminated from that direction. A separate set of six coefficients is fitted to the image data for each pixel and stored as a spatial map, which has the same spatial resolution as each of the original *n* images, but has a low resolution in the angular space of the incident illumination, because the *n* directions of the



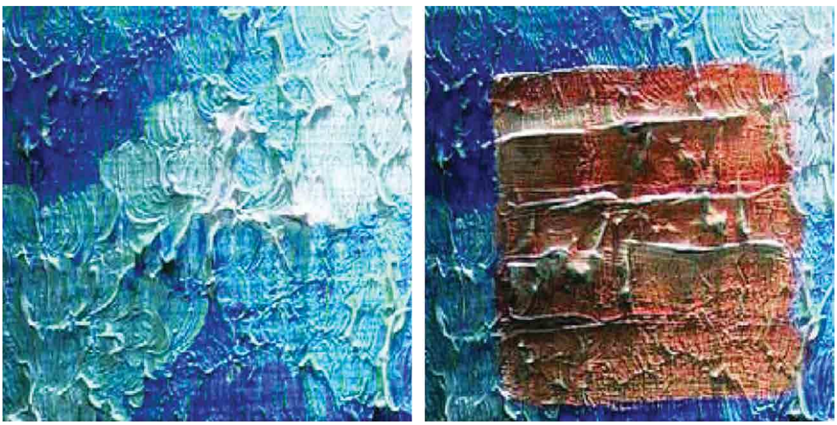


Figure 20.1.
Left: experimental apparatus for PTM at the National Gallery (London) with twenty-four tungsten spotlights mounted on a rigid framework. Below: surface relief of a painted test panel, lit from the top right. © Joseph Padfield, National Gallery, London.

image set are approximated by only six coefficients at each pixel. An improved set of basis functions, known as hemispherical harmonics (HSH), was introduced by Gautron et al. (2004), which gives a better estimation of intensity as a function of angle, at the expense of additional parameters. The interactive control of lighting direction in the viewer software facilitates perception of the surface structure compared to static photographs, thereby enhancing the legibility of surface relief and inscriptions. The visual effect is of a virtual torch moving over a static 3D object surface, although there is no inherent 3D geometry.

Key to the broader adoption of RTI has been the development of Highlight-RTI, in which a glossy sphere is placed in the scene so that the direction of the incident illumination can later be inferred from the coordinates of the highlight in each image. The H-RTI method was introduced by Mudge et al. (2006) for on-site imaging of rock art. The feature is that the illumination source, such as a flash or spotlight, can be moved freely to any position above the surface for each image, with no predetermined constraints and also no specific recording of its position. H-RTI obviates the need for a dome system, and enables the photography to be done *in situ*. Such a technique is essential for field work where the objects are so large or impossible to move that there is no alternative but to do the imaging on site, such as monuments, caves, and excavations. A good review of applications in archaeology is given by Earl et al. (2010), and a guide to good practice may be found in Duffy (2013).

All methods of PTM and RTI capture rely on knowledge of the light positions used to illuminate the object. For a dome system this is determined by the physical placement of the lights. Alternatively a template might be used to determine the exact positions of one or more movable lights in predetermined locations. An equivalent would be to employ a robot arm to position a lamp successively at pre-programmed locations. Equipment with fixed lighting positions has many advantages, including speed of acquisition, accuracy, and repeatability. But it also has limitations, in particular the maximum object size, cost, portability, and difficulty of adapting to the site topography.

PTM and RTI have found favour with the cultural heritage community because they provide a convenient and attractive way to visualize artefacts and simulate the three-dimensional effect. The interactive control of lighting direction in the viewer software facilitates perception of the surface structure compared to static 2D photographs, thereby enhancing the legibility of relief and inscriptions. The set of images affords a richer representation of the object surface than a single image and could therefore be considered as a new data type for the documentation of collections of cultural heritage objects.

Significant Applications

Example 1: Painting Texture, The National Gallery, London

PTM was applied in 2004 at the National Gallery in London to investigate the surface structure of paintings by Frans Hals, Jules-Louis Dupré, and Georges Seurat. Twenty-four tungsten lamps were mounted onto an open framework in three tiers of eight lamps each (fig. 20.1, left). The camera was mounted at the top of the framework, pointing down at the painting on the floor. The lamps were turned on and off manually for each image in the sequence to be captured. With the variable "virtual light" in the PTM viewer more features were visible than could be seen by raking light from one direction alone, enabling the study of surface features in the painting such as impasto (fig. 20.1, right) and also the effects of ageing, such as craquelure and distortion of the support. Comparing PTM renderings made before and after physical handling of the painting facilitated examination of alterations in its texture and shape (Padfield et al. 2005).

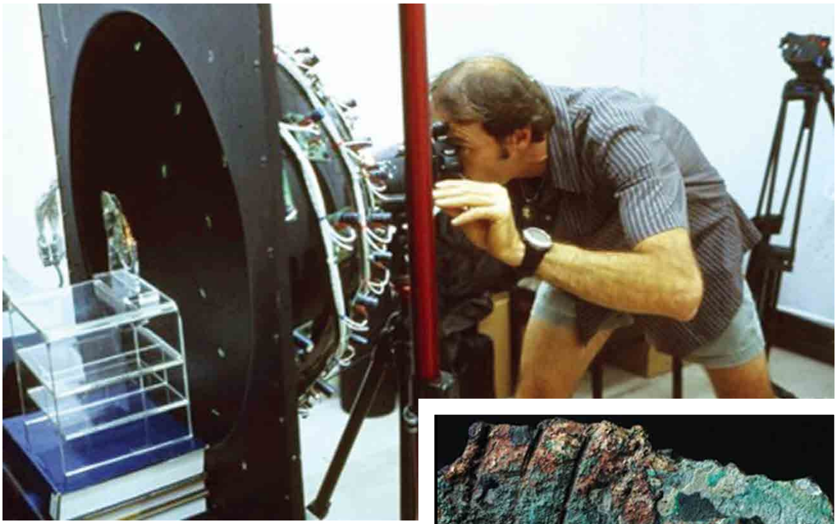


Figure 20.2. Above: Malzbender using his illumination dome in an upright orientation to image a fragment of the Antikythera Mechanism. © Tony Freeth; Right: PTM reconstruction of fragment 31, with "specular enhancement," showing scales and inscription. Screen grab from PTM viewer © Hewlett-Packard.

Example 2: Inscriptions on Antikythera Mechanism, National Archaeological Museum, Athens

In a famous investigation in 2005, PTM was used to acquire image sets of the fragments of the Antikythera Mechanism at the laboratories of the National Archaeological Museum in Athens. Named after its place of discovery in 1901 in a Roman shipwreck, the Antikythera Mechanism was constructed ca. 200 BC but is technically more complex than any known device for at least a millennium afterwards and indications are that Archimedes was involved in its design. Because the fragile fragments could not be taken out of the museum, the PTM dome was taken there and used in a vertical orientation in front of the camera on a tripod (fig. 20.2, left). Samples were carefully positioned on holders to enable the imaging to be done without any physical contact. The resulting eight-two image sets have been used for analysis of the inscriptions (fig. 20.2, right), enabling a better understanding of the structure and function of the mechanism (Freeth et al. 2006).

Example 3: Prehistoric Rock Art at Roughting Linn, Northumberland

Sarah Duffy in 2009 used RTI in a daytime survey of rock art at Roughting Linn, which is considered the largest decorated rock in northern England, originated in the Neolithic and Early Bronze Age. The H-RTI capture method was used with a Canon 22mpx EOS-1Ds Mark III camera and wireless remote-controlled flash, Manfrotto tripod, two black snooker balls, scale ruler, and 18 per cent grey card. One person operated the camera by remote control, while the other held the flash to illuminate the rock surface. A piece of string was mounted on a thin piece of PVC pipe so that the person positioning the light source was able to hold both the flash and the end of the string. Logistical challenges included daytime lighting, windy conditions, and the relatively remote location of the site. To lessen the effects of the daylight, filters were fitted to the camera lens. Additionally, weights were added to the tripod to offset the wind and to stabilize the camera during photography. There was no access to mains electricity, so all the equipment was self-powered and kept properly charged. Multiple PTMs were generated from the data sets gathered through the fieldwork, and were incorporated into the English Heritage site documentation. The PTMs provide additional interpretive insights, with the potential to answer questions about relative chronology, tooling techniques and instruments, and the stylistic programme.

Figure 20.3. Left: on-site photographic recording in process at Roughting Linn. Top right: traditional static photograph of carving. Bottom right: screenshot of PTM viewed with specular enhancement. © Sarah M Duffy.

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* Essential texts

STRUCTURE FROM MOTION

see also PHOTOGRAMMETRY

MONA HESS and SUSIE GREEN

COSCH Case Studies that have employed this technology: Roman coins, Germolles, Kantharos, Bremen Cog

Definition

Structure from Motion (SfM) uses the principle that movement through a scene allows an understanding of the shape of objects within the scene in three dimensions, in the same way as walking through a room allows one to visualize the space and objects within it. In SfM the movement is represented by a series of systematic viewpoints; overlapping photographs taken from different locations around the object. This can be achieved from the ground in the field, in a photo studio, or from the air with a drone or other unmanned aerial vehicle (UAV).

Description

SfM is a method of photogrammetric recording. It is used for area-based recording and for object recording. A series of single images are photographed and the reconstruction of the 3D model uses similar steps to a photogrammetric workflow with orientation through image point comparison and bundle adjustment, measurement and analysis based on internal and external geometry, possibly using image masking, and output of a coloured point cloud or polygon mesh. Workflows include the combination of free software for photogrammetry, or licensed but affordable software, increasingly tailored for easy use. Whereas photogrammetry was previously used to measure a set of discrete points, typically using markers placed on objects within the scene, SfM extends the method (without the need for markers) by automatically finding feature correspondences and using dense matching techniques to reconstruct complete surfaces. The drawback is that where photographic coverage is poor the point clouds generated by SfM may be quite noisy and have “holes” in the surfaces represented by the point clouds, requiring subsequent smoothing and filling operations.

Figure 21.1. Edinshall kite aerial photography. Photo: Susie Green, 2011.

SfM can be used for the archaeological investigation of landscapes and built structures. The use of a kite or UAV can enable coverage of a large area in high resolution, allowing earthworks to be traced across the landscape. When used in conjunction with an archaeological excavation, its simplicity, low cost, high coverage and speed of recording, allows individual aspects of the 3D data to be analysed in ways that are simply not possible with 2D records. The amount of detail that can be captured makes this an ideal means of recording features that could be damaged or destroyed, such as fragile wooden objects, landscapes that are to be developed, or stratigraphic layers that must be removed. Similarly, the speed at which data can be gathered makes this a potentially important tool for the recording of underwater archaeology.

The recording of surface colour, as well as form, by SfM enables the creation of photorealistic 3D models at high spatial resolution. Such models are popular and powerful tools for disseminating archaeological ideas to the public.

For finds and smaller objects, examples of morphometric analysis and comparative taxonomy by SfM models contribute to scientific research projects (Bevan et al. 2014). Whilst SfM works well on its own, often a combination with other recording techniques yields better results (MacDonald et al. 2014). SfM can be used to record high-resolution 3D digital surface models of museum objects of all scales and materials, in the round, to scale and with the option to include calibrated colour mapping. The technique can be used with little training, and free software tools allow the reconstruction of the 3D surfaces, online or on a local desktop computer or laptop. One software package that has become popular in recent years is

Figure 21.2. Edinshall georeferenced colour map derived from point cloud. Photo: Susie Green, 2011.

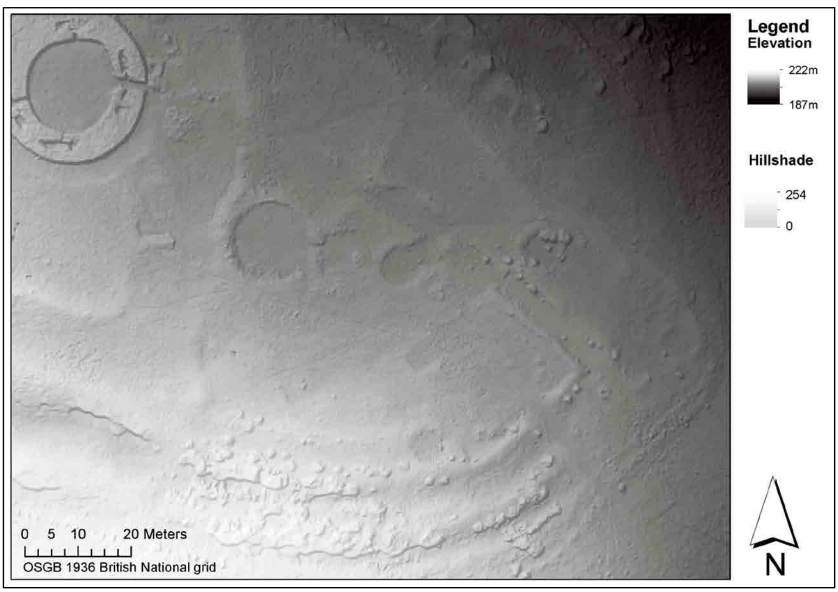

Figure 21.3. Edinshall georeferenced elevation map derived from point cloud. Photo: Susie Green, 2011.

Agisoft PhotoScan. Such digital 3D models can be used for online dissemination, teaching in the classroom and for creating physical reproductions by 3D printing.

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Example of Application

SfM with UAV for Archaeological Research

Edinshall in Berwickshire, Scotland, consists of a double rampart iron age hillfort, within which there is a broch (also known as an Atlantic roundhouse) and evidence of a settlement, dating from the second half of the first millennium BC through to the period of Roman occupation. The hillfort is approximately 140 m by 100 m. Edinshall was photographed using a remote-controlled camera rig attached to a kite in June 2011, following an unusually dry spring, which enabled the earthworks to be seen as crop marks where the grass was dry.

Using SfM a 3D point cloud of the hillfort ground surface was created from the photographs and georeferenced using Ordnance Survey maps. The points were then loaded into ArcGIS and used to create a digital elevation map using the Z coordinate of the points to represent height, and a colour map taking the colours from the points. These maps have a resolution of 5 cm, which is sufficient to pick out individual stones and the paths left by animals. The height map and elevation map are derived from the same data so the elevation details can be directly compared with the crop marks. The time taken to create these maps, the cost of equipment and results achieved compare very favourably with the traditional method of topographic survey.

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STRUCTURED LIGHT 3D SCANNING

DIRK RIEKE-ZAPP and SANTIAGO ROYO

COSCH Case Studies that have employed this technology: Roman Coins, Kantharos, White Bastion

Definition

Structured light 3D scanners project a known pattern of light (stripes, dots), typically regular and periodic, onto the object. The result is captured using one or more cameras, and the 3D information of the object is recovered by software using different triangulation or projection geometries. Very dense and accurate point clouds may be obtained. The configuration and approach used enables adjustment of the surface resolution, using multiple exposures, or adjusting the field of view of the system.

Description

A structured light 3D scanning system is non-contact and consists of a projector and at least one camera. Data acquisition and analysis are controlled by dedicated software running on personal computers; both are integral parts of the measuring system. The calculation of 3D data is based on the triangulation principle; typical triangulation angles are approximately 30°. The camera is mounted in a calibrated position relative to the projector, and the scanning system projects light patterns onto the object surface. The contrast of the light patterns influences the quality of scan results. Therefore, working in direct sunlight is often not possible or advisable. For good results, working indoors or in shaded areas outdoors is recommended. Scanning of reflective or (semi-)transparent surfaces is problematic for any optical scanning system. Difficult surfaces include shiny metal, glass, marble, bones, teeth, and many plastic materials. Covering the surface with whitening spray eliminates reflection or transparency problems, but is not applicable to all objects. Scanning critical objects that may not be spray-coated is often possible

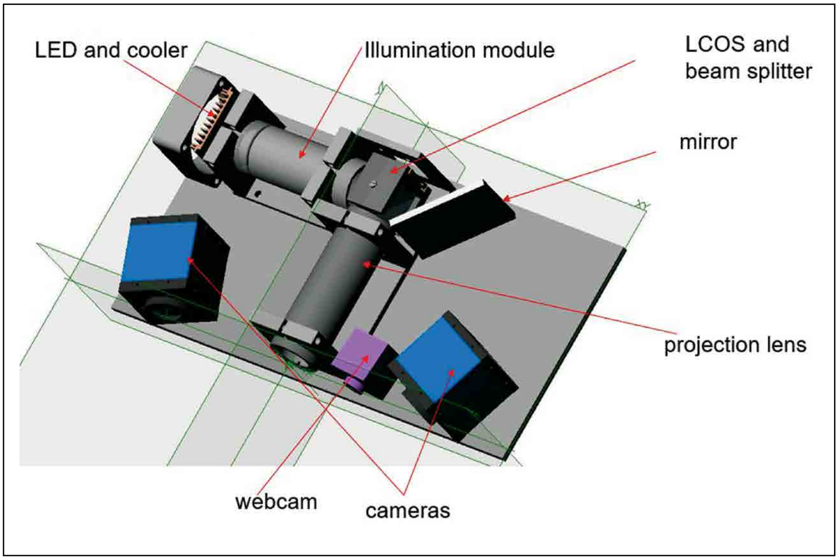

Figure 22.1. Schematic of a typical compact structured light scanner with two cameras (webcam only for alignment) developed by the Centre for Sensor, Instruments and System Development at the Universitat Politècnica de Catalunya (UPC-CD6). © UPC-CD6, 2010.

with additional effort, by further scan positions or angles, user interaction or software filtering.

The object size covered in a single scan is limited by the projector's brightness as well as the feasible distance between projector and camera. The field of view for a single scan setup typically ranges from 30 mm to 2000 mm; the camera system's depth of field determines the system's measuring depth. Furthermore, there is a link to depth resolution, as larger areas imply lower resolution/accuracy because spatial resolution is dependent mostly on the number of samples per unit distance, so denser sampling means, in most approaches, a better depth detail under comparable angle of view (disparity) conditions. Larger or complex objects are captured by multiple scans that are aligned and merged into a single 3D model by dedicated software, which may include acquisition of the same area under different scales for more complete documentation. Thermal instability of the projector can be compensated for by adding a second camera for stereo measurement (see fig. 22.1 for a typical arrangement). The projector usually works with light in the visible spectrum or the near infrared. Most industrial fringe projection systems employ the short wavelength of blue light, which produces better scanning results on semi-transparent or reflective objects and allows better control of

Figure 22.2. Compact structured light scanner with stereo camera system. © AICON 3D Systems GmbH, 2016.

Figure 22.3. Cross of the Scriptures, Clonmacnoise, Ireland. Source: 3D ICONS Ireland, www.3dicons.ie/3d-content/52-cross-scriptures-clonmacnoise, reproduced under CC www.3dicons.ie/process/licensing.

ambient light. Some structured light systems project patterns in the near infrared spectrum, making them invisible to the human eye. Monochrome cameras capture more light per pixel, produce less pixel noise, and thus ensure better 3D data quality than colour cameras. Scanning systems with colour cameras on the other hand have the advantage that shape and colour are captured at the same time. Scanners with colour cameras are only available with white or infrared light projection.

A basic structured light system projects a single random, binary pattern. Image correlation techniques are used to identify these patterns in the camera image for calculation of 3D coordinates. Data acquisition of structured light systems is fast and suitable for dynamic measurements. Correlation of image patches results in significantly lower 3D resolution compared to image pixel resolution, fine details like steps or edges are captured with medium fidelity. Background illumination and contrast are not separated for analysis of the scene. Structured light systems are often used for digitization tasks and medium accuracy control measurements. The output data is typically saved as point cloud information.

A special configuration of a structured light system is the fringe projection system, which projects a sine wave variation of multiple fringes onto the object surface. The camera records projected patterns that may consist of different combinations of coded patterns or a variety of fringes with different phases, enabling the application of different types of phase-shifting algorithms for improving accuracy and yielding dense sampling. A fringe projection system provides a single 3D reading per pixel and resolves fine details with very high fidelity. The projection of multiple patterns separates scene contrast and ambient illumination from the object, allowing for better control of background illumination. Data acquisition by fringe projection systems is slower than with single-shot systems. The acquisition time of fast fringe projection sequences ranges from 1 s to 0.01 s, depending on projection speed and surface properties. Fringe projection systems are well established for the 3D digitization of complete surfaces as well as for high-resolution scanning of small to medium-sized objects (fig. 22.2). The output data are typically saved as a point cloud or triangulated mesh. An internationally recognized standard for accuracy assessment of optical 3D measuring systems based on area scanning is given by VDI/VDE 2634, Parts 2 and 3.

Significant Applications

3D-ICONS Project Guidelines and Case Studies

- http://3dicons-project.eu/eng/Guidelines-Case-Studies
- 3D-ICONS Portal, http://3dicons.ceti.gr.

Structured light scanners were used for short-range, small-scale cases, for example The Market Cross (Glendalough, Ireland) and the metope "Suicide of Aiace" (Paestum, Italy). 3D-ICONS is a large database of several cultural heritage objects scanned using several techniques including structured light. http://3dicons.ceti.gr.

3D-MURALE—3D Measurement and Virtual Reconstruction of Ancient Lost Worlds of Europe

- http://cordis.europa.eu/project/rcn/52648_en.html

A combination of techniques including active illumination for 3D reconstruction was used to recover different scales of detail, combined with texture analysis.

The CultLab3D Project

- www.cultlab3d.de/results.html

Combination of different aspects related to 3D scanning of cultural heritage objects to provide a general-purpose digitization tool for small objects in Museums

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TOTAL STATION SURVEYING

MASSIMILIANO DITTA and AMANDINE COLSON

COSCH Case Study that has employed this technology: Bremen Cog

Definition

A total station is a surveying instrument using laser light. The distance between the instrument and the target is measured and recorded digitally. It is considered a direct surveying technique because the operator chooses the acquired points manually and defines them in advance. The degree of accuracy of each point remains high, but the global accuracy of the acquisition varies depending on the operator's methodology applied in a given context. A multitude of points, called a point cloud, will be produced providing geometrical data. This technique is very often used on building sites, as well as on archaeological excavations to measure large distances and establish maps.

Description

The total station is a composite technology, which allows selective recording of 3D coordinate points without direct contact between the instrument and the subject. The device integrates the functions of a theodolite (transit) for measuring angles, with an electronic distance meter (EDM) and a digital recorder. Angles and distances are measured from the total station to points under survey, and the spatial coordinates (X, Y, Z) are calculated using trigonometry and triangulation. The final output is a sequence of points with three-dimensional coordinates in relation to a local or geographical reference system.

The user has no visual feedback or control of the ongoing acquisition, until the process is completed and the data stored on the internal memory. However, there is a different way of using this instrument, as demonstrated in the COSCH case study of the Bremen Cog (chapter 7). The setup introduces a new element in the workflow, consisting of data acquisition, in real time, through software which enables a direct communication between the total station and the host computer. The innovation lies in the use of 3D CAD software (Rhinoceros 3D) which can communicate directly with the total station through a plug-in, Termite, developed by Frederick Hyttel, a former student of the Maritime Archaeology Programme in Esbjerg, University of Southern Denmark. The most useful feature of Termite is the ability to resect the total station data on the fly. "Resection involves the computation of instrument position via observation of two or more reference marks or stations of known position. . . . Once the instrument has been moved to a new position, these marks can be re-observed to determine the new station coordinates" (Andrews et al. 2009, 9). The most troublesome aspect of total station recording is the necessity to record from several positions, whereas Termite allows all the data to be recorded in a single file, and then to keep that file updated with the total station's location and orientation (Hyttel 2011). For setting up the system, two sets of data are needed: (1) reference points; (2) target points. The network of reference points is necessary for establishing the positions of the total station and the subsequent resections, as well as to continue the monitoring over time. Suitable stations for the positioning of the total station must fit with two main requirements: a clear sight of at least four reference points, and a visual contact between the target or reference points and the total station aiming cross between a 90° and 45° angle. Ideally, if the referencing network remains in place, the same file may be used for subsequent acquisitions, and no errors will be added to the existing network.

The recording of both reference and target points was carried out with the Leica TS06 in reflector-less mode set on "fine," thus with a linear accuracy of ±2 mm + 2 ppm at 200 m (Leica ScanStation P20 2013). The angular error for the Leica TS06 is five. The maximum operative distance between the total station and points is less than 25 m. The maximum difference between the coordinates of two points was ±0.03 mm, far beyond the total station's own certified accuracy. Therefore, it can be stated that, taking into account both the resection and the angular errors, the measurement noise is expected to fall well below 1 mm.

Significant Applications

Since 1999, the Vasa Museum in Stockholm, Sweden, has been using a total station to monitor the deformation of their sixteenth-century, 69 m-long wooden ship, known as the Bremen Cog. The survey methodology was designed by Milan Horemuž from the Royal Institute of Technology in Stockholm, in cooperation with the team of the Vasa Museum, and the archaeologist Jacob Jacobson. Two campaigns per year enable the change in shape (Jacobson 2003, 186 and 188) to be measured. The 3D data are processed and visualized in a programmed platform in

MATLAB, including environmental information such as temperature and relative humidity collected by other sensors in the exhibition room (Horemuž 2003, 5). The acquisition includes 301 targets on the hull taken from sixty-six positions (van Dijk et al. 2016, 106).

In the field of cultural heritage, the total station is used daily all over the world in archaeological excavation (Howard 2007, 3) and for historic buildings (Lane 2016, 15) as a standard measurement tool. The recording of the Khaplu Palace located in northern Pakistan gives a concrete example of the use of a total station to document architecture. The information acquired constituted the basis of a large conservation and restoration programme (Muhammad 2011, 74) funded by the Aga Khan Trust for Culture that started in 2005. Combined with the local building traditions, the survey was both more accurate and less time consuming than manual sketches (Muhammad 2011, 76). The palace was fully restored in 2011 and has since become a luxurious hotel.

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X-RAY FLUORESCENCE (XRF) SPECTROMETRY

JULIO M. DEL HOYO-MELÉNDEZ

COSCH Case Studies that have employed this technology: Roman coins, Germolles

Definition

XRF spectrometry is a non-destructive analytical technique widely used to determine the elemental composition of materials. It has been demonstrated to be effective in fields including biology, medicine, geology, material science, environmental studies, and cultural heritage, among many others. The suitability of this technique for conducting elemental surveys that require no extraction of samples makes it very versatile in cultural heritage research.

Description

X-ray fluorescence is induced when photons with enough energy, emitted from an X-ray source, interact with a material. High-energy photons induce ionization of inner shell electrons through the photoelectric effect, creating electron vacancies in these shells. These vacancies are almost immediately filled with electrons from outer shells resulting in emission of fluorescent radiation, which is characteristic for each element. The lines observed in the XRF spectrum enable identification of the chemical elements present. XRF analysis is therefore a powerful analytical tool for the spectrochemical characterization of most elements present in an object.

An XRF spectrometer contains several components including: an excitation source or X-ray tube, a sample chamber or open shutter system to deliver X-rays to the sample, a detector to determine the characteristic X-rays generated, an analyser that converts the measured energies to their correspondent electronic transitions, and a display device to visualize the measured spectra. Early XRF instruments contained a sample chamber, typically of limited size, that allowed only for the measurement of samples extracted from cultural heritage objects. In response to the needs of heritage scientists, modern instruments employ open beam systems that allow simultaneous X-ray irradiation and detection of fluorescence emitted by actual historic objects of all sizes without requiring sampling. The detector is composed of two charged electrodes that have a non-conducting or semi-conducting material positioned between them. The X-rays ionize these materials causing them to become conductive. The unbound electrons are accelerated toward the detector anode to generate a signal that can be measured. Based on the detector used, X-ray techniques can be divided into energy (EDXRF) and wavelength dispersive (WDXRF).

Two types of analysis are possible in XRF. Qualitative analysis allows identification of the elements present in the object, and has been used on paper artworks, paintings, and ceramics. Quantitative analysis involves the determination of the relative amount of each element present in an object. Since the material must be infinitely thick to X-ray penetration, the number of heritage objects that can be quantitatively analysed is very limited. Typically, we consider the "infinite thickness" of a sample as the thickness from which 99 per cent of the intensity of a given element (analyte) is collected. The thickness of a material can only be estimated for values lower than this limit. It is important to notice that this infinite thickness depends on the X-ray penetration and absorption. For this reason when performing quantitative analysis it is better to consider the higher energy/penetration lines for a given element. In the case of silver, a K line has an approximate penetration of 100 microns while the L (lower energy) penetrates to about 10 microns. Therefore, the signal arising from the layer of higher penetration (K line) is used. Quantitative analyses are typically conducted on metal objects and the results are usually expressed in weight percentage of detected elements. However, it is important to emphasize that XRF is a surface technique and factors such as non-homogeneity, enrichment, and corrosion can lead to results that can deviate significantly from quantities in the bulk. Generally, the original composition of a historic metallic object can be determined by studying the composition of the bulk. This typically requires extraction of samples or the use of destructive analytical techniques. Therefore, when using surface methods such as XRF the information could be limited to the first micro-layers of the object.

XRF reports typically include the instrumental parameters and spectrometer model used, the elements detected, the level of confidence, the elemental concentration (if applicable), the calibration method used, and the estimated error. The use of synchrotron radiation and scanning systems (macro-XRF) are relatively recent developments that have provided great advances in the cultural heritage field. Most cultural institutions use XRF spectrometry together with complementary techniques such as Fourier transform infrared (FTIR) spectroscopy, Raman spectroscopy, X-ray diffraction (XRD), and most recently multispectral (MSI) and hyperspectral imaging (HSI) techniques.

Significant Applications

Early investigations involving the use of XRF for analysing cultural heritage materials date back to the 1950s. The work of Kraay (1958) on the determination of the composition of electrum coinage offers a good example of innovation in applying the technique to numismatic research at that time. More recently, Linke et al. have made significant advancements in the application of XRF to the study of numismatic collections. The authors evaluated the advantages and limitations of the technique when conducting qualitative analysis of metal alloys and also described surface effects that can lead to misinterpretation of the results. Special attention has been paid to silver surface enrichment effects observed in historic coins made of silver-copper alloys (Linke et al. 2004). Although small objects such as coins can be easily transported to the laboratory, this is not always the case for larger objects whose movement may be restricted. Therefore, the cultural heritage field has benefited from a series of technological developments in XRF spectrometry that have taken place over the past years. The development of portable XRF instruments that make use of thermoelectrically-cooled detectors and miniaturized X-ray tubes has resulted in broader applications of the technique to study a larger range of objects. These developments have had a significant impact in archaeological and art-technological research conducted either in the laboratory or on site. Nowadays, XRF spectrometry has become a standard analytical tool in museums, research institutes, and universities.

Important applications in the field of archaeological research include: soil analysis for evidence of human activities (Pastor et al. 2016), sourcing of obsidian and other lithic materials (Craig et al. 2007; Frahm 2014), study of ceramics (Pincé et al. 2016), and identification of pigments (Shoval and Gilboa 2016). However, several controversial issues regarding the interpretation of XRF results in archaeological research have been highlighted recently. For example, the use of the technique for obsidian sourcing has been a subject of debate among researchers (Frahm 2013; Speakman and Shackley 2013). The scepticism has arisen because a group of researchers believe that the results have low accuracy and precision, and that calibration and correction factors have been wrongly applied. There have also been claims that researchers show little knowledge about fundamental XRF issues such as sample size restrictions and morphology effects (Frahm 2013). On the other hand, Speakman and Shackley (2013) point out that their critics do not take into consideration the importance of following standard analytical protocols in order for the results to be verifiable by other researchers. This is a subject of ongoing debate and further research and discussion will help to advance the field of archaeometrical analysis.

In the art technological field, XRF has undergone a significant evolution as a result of the integration of scanning devices. Macro-XRF instruments are increasingly employed in cultural and research institutions to scan the surface of large 2D objects. In this respect, the work of Alfeld can be considered pioneering due to the development of the first XRF scanner used for visualization of hidden paint layers. These instruments are capable of imaging the distribution of the main elements present in surface and subsurface paint layers. The interesting visualization of underpainting in a work by Rembrandt van Rijn using macro-XRF were reported by Alfeld et al. (2013). The authors demonstrated that this approach can be quite promising in situations where neither infrared reflectography nor neutron induced autoradiography can be used as visualization tools for revealing underpainting.

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