Chapter 3

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

ANNA BENTKOWSKA-KAFEL,
VERA MOITINHO DE ALMEIDA, LINDSAY MACDONALD,
JULIO M. DEL HOYO-MELÉNDEZ, and AURORE MATHYS

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.

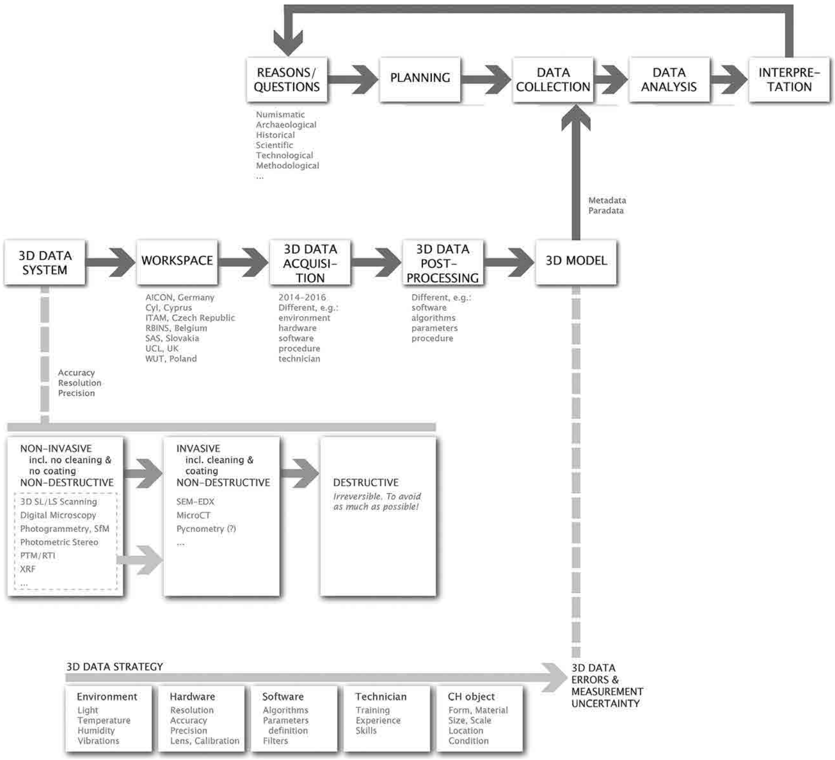


Figure 3.4. Proposed methodological framework for the 3D digital data acquisition, processing, and analysis of historical silver coins. © Vera Moitinho de Almeida, 2016

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.

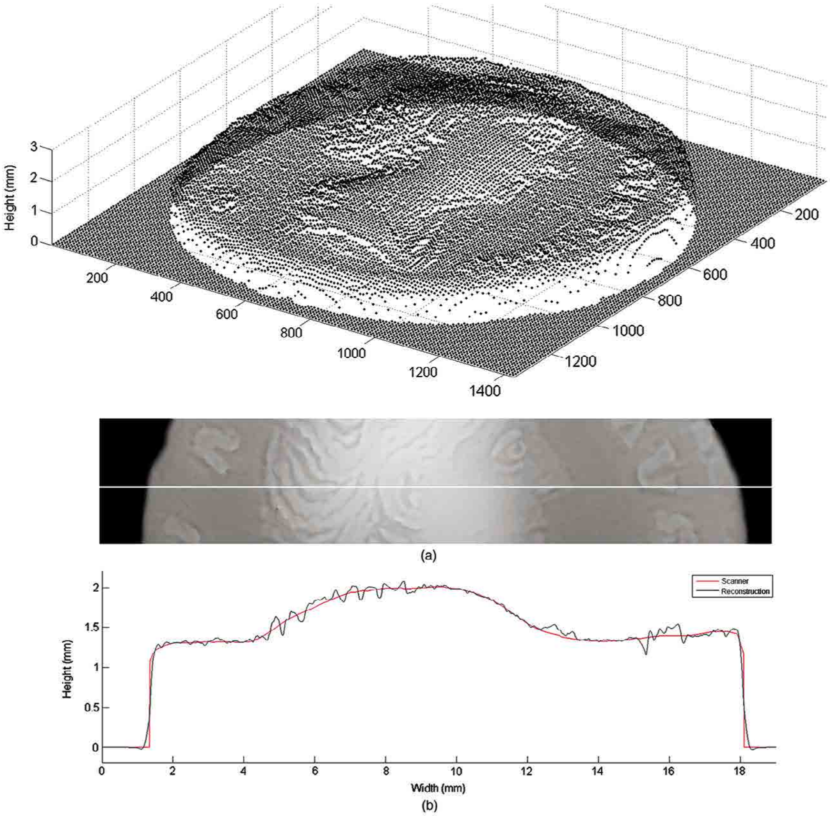
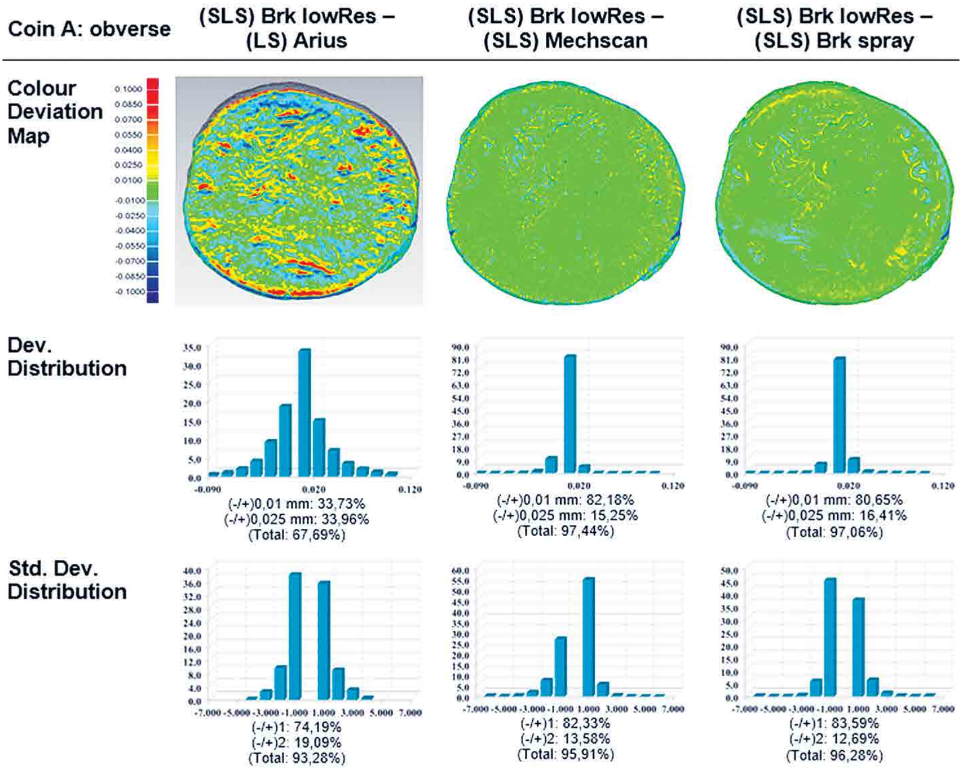


Figure 3.6. 3D reconstructed surface based on photometric stereo. Horizontal section with elevation showing (a) laser scanner height and (b) reconstruction. © Lindsay MacDonald et al., 2017.

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

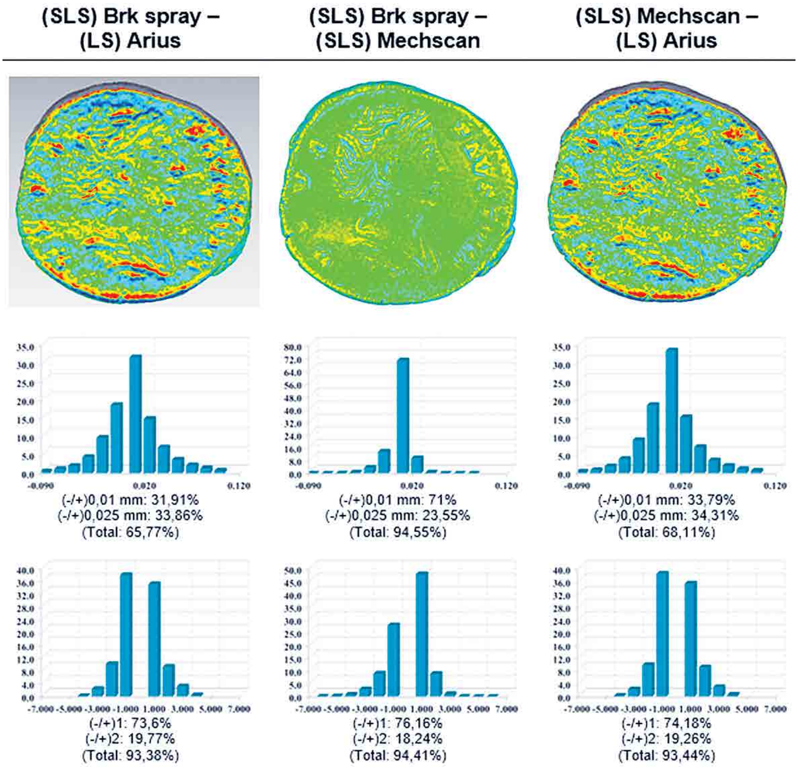


Figure 3.7. Results of the deviation between the obverse of the 3D models of coin A: colour deviation map, deviation distribution of points, and standard deviation of points. © Vera Moitinho de Almeida, 2016.

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. © Vera Moitinho de Almeida, 2016.

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** (mm^2)	**Volume** (mm^3)	**Peri-meter** (mm)	**Shape factor**	**Density** (g/cm^3)
–	–	–	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

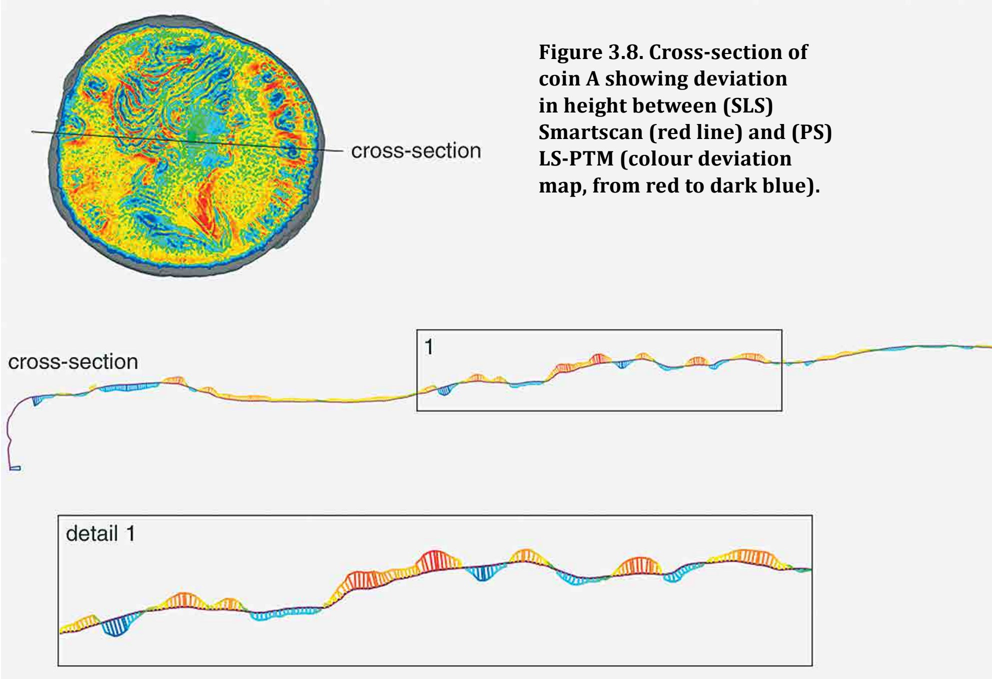


Figure 3.8. Cross-section of coin A showing deviation in height between (SLS) Smartscan (red line) and (PS) LS-PTM (colour deviation map, from red to dark blue).

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.

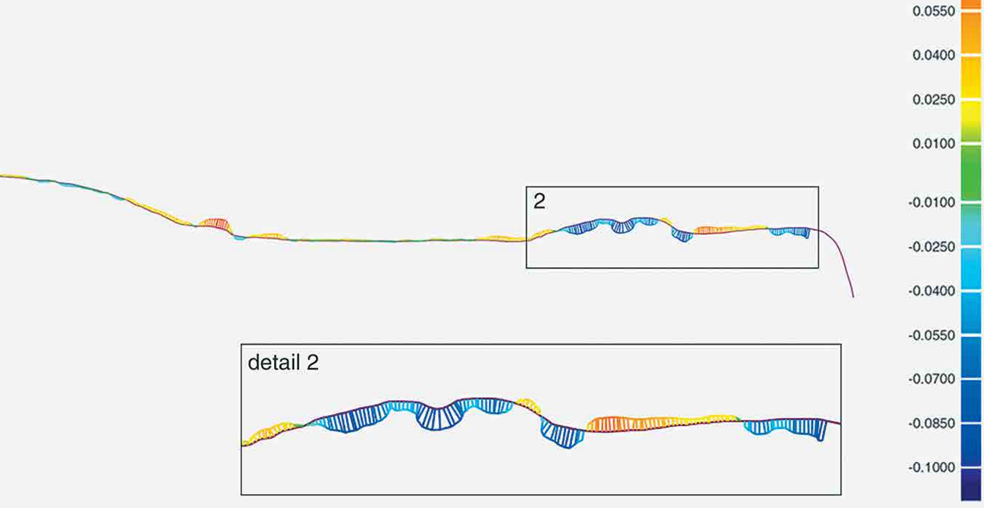


Table 3.6. A map of atomic composition of coins based on EDX analysis in SEM. The composition of the denarii of Faustina the Elder (A) and (B) is compared to two further denarii of Republican Rome (C) and Emperor Vespasian (D). The results at two measurement points are shown for each coin. The two grey 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/.

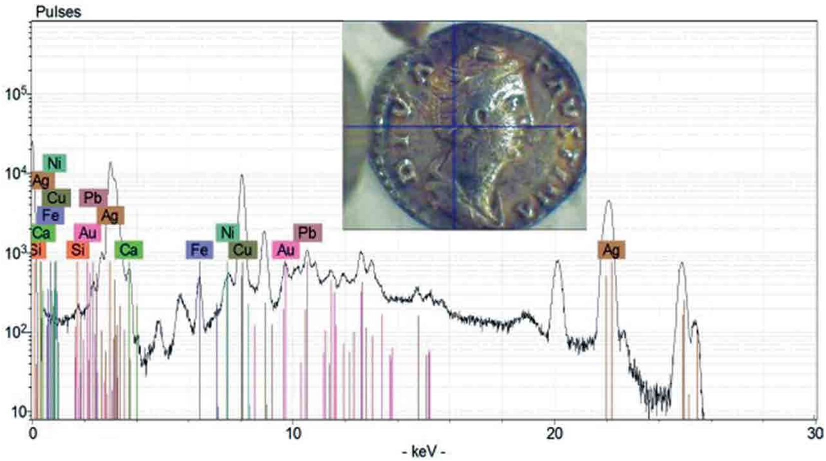


Figure 3.9. Micro-XRF spectrum of the point shown in the inset for the obverse of coin B. Unidentified peaks are likely due to three factors, namely interactions in the detector, X-rays contributed by the analysis system, and X-ray interactions in the sample. © Julio M. del Hoyo-Meléndez, 2015.

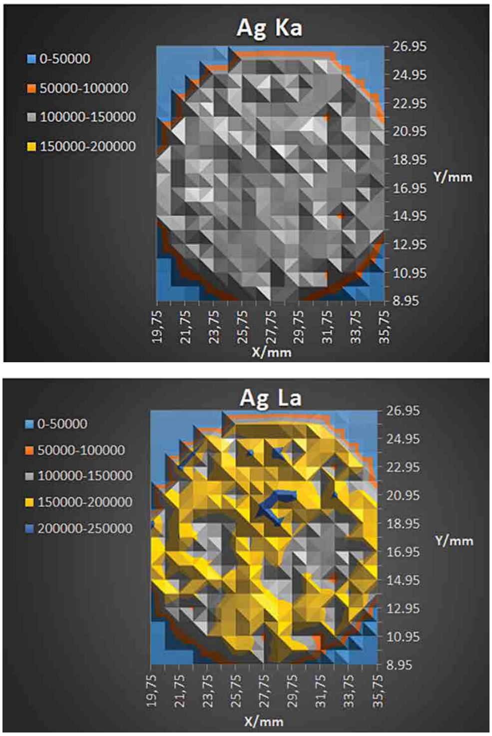


Figure 3.10. Elemental maps obtained by the Artax 800 instrument for the obverse of coin A showing Ag Ka (top) and Ag La lines (bottom). Although the map obtained for the Ka line shows that the coin is rather homogeneous, the less penetrating La line shows an uneven surface most likely associated with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

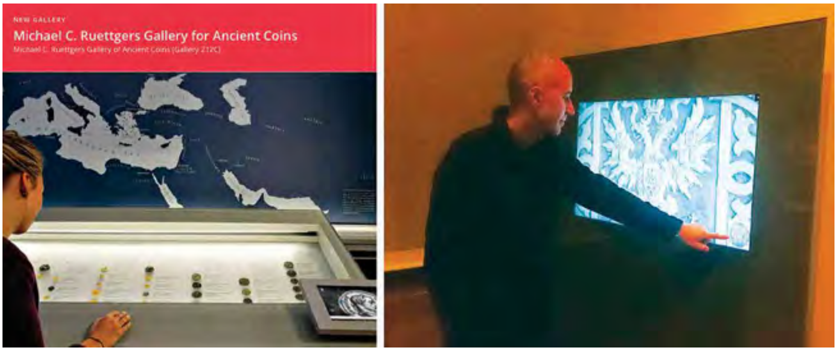


Figure 3.12. Multimedia displays provide a vehicle for dissemination, *in situ* and online, of rich information about the object, its scholarship, and heritage science. Numismatic galleries of the Museum of Fine Arts, Boston, MA (left) and the Hutten-Czapski Collection, National Museum in Kraków, Poland (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.

This page intentionally left blank.