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Depth and Dimension: Exploring the Problems and Potential of Photogrammetric Models for Ancient Coins

RESEARCH ARTICLE

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ABSTRACT

In numismatic collections, coins are typically documented and studied using 2D images of their obverse and reverse. While two photographs, under the correct lighting, provide adequate information for basic research, detailed numismatic study has generally required the physical handling of the items to capture the three-dimensional aspects of the coin. Recent advances in photogrammetry and digitisation provide new opportunities for numismatic research. Digitised, 3D models of ancient coins allow researchers and students to interact with these coins remotely, providing opportunities to study coins from collections that would otherwise be difficult to access. Ancient coins, however, can be challenging to digitise due to their small size, irregular shape, and reflectance. This study will explore and outline a methodology for creating 3D models of ancient coins that balances both expediency with quality. Three Roman Republican coins from the University of Auckland's numismatic collection were digitised using photogrammetric methods to create 3D digital models for student use. Expedient capture relied primarily on the quality of the photogrammetry setup, as well as the use of macrophotography, to capture the detail of each coin effectively. While the digital models took longer to produce than traditional 2D images, it was possible to create high-quality digital 3D model coins in a relatively expedient manner. The balance between speed and increased data opens the door for a new era in numismatic cataloguing and qualitative research opportunities.

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1.0 INTRODUCTION

The use of 3D digitisation techniques to catalogue and study ancient artefacts has gained significant traction in recent years. Photogrammetry, in particular, has seen a noteworthy rise to prominence, whereby a 3D model of an object is created by capturing many images under correct lighting and at various angles. These 3D models of ancient artefacts are utilised in many areas of archaeological research including underwater archaeology (Kalinowski, Nietiedt & Luhmann 2021), museums and heritage (Emmitt et al. 2021), and pedagogy (Wyatt-Spratt & Thoeming 2019). Recent advances in digitisation provide ever-increasing opportunities for accessibility and teaching as these 3D models can be studied remotely. Artefacts best suited for 3D modelling have structured surfaces and many edges, while unstructured and reflective artefacts can be problematic to capture. It is of little surprise, then, that ancient coins have not received the same attention as other classes of artefacts within the field of 3D modelling (Hess, Macdonald & Valach 2018; Macdonald, Moitinho & Hess 2017; Mara et al. 2007). Ancient coins are small, with varied shapes and sizes, and are highly reflective, making them especially challenging to capture using photogrammetry.

The widespread creation of 3D coin models, however, would provide an invaluable tool for researchers throughout the world. Coins can be found in public and private collections, and arguably represent the most widely accessible and easily identifiable type of artefact from the ancient Mediterranean region. Traditionally, coins are studied and catalogued using 2D photographs of their obverse and reverse. Since the early 20th century, 2D images have been used in catalogues of ancient coinage, such as the *Historia numorum, a manual of Greek numismatics* (Rutter 2001), the multi-volume *Roman Imperial Coinage* (Mattingly et al. 1920–2008), and Crawford's *Roman Republican Coinage* (Crawford 1974), to complement written descriptions and commentaries on coins. Recent major online catalogues, including *Coinage of the Roman Republic Online* (CRRO), *Online Coins of the Roman Empire* (OCRE), and the American Numismatic Society's online MANTIS database all utilise, and sometimes explicitly replicate, the same basic system. As coins are generally disc shaped, two photographs, under the correct lighting, provide a convenient means of documentation while still providing quite a lot of information. However, this system is recognised as a compromise, and 'proper' numismatic study has generally required the physical handling of the items (Mudge et al. 2005). Coins are three dimensional, physical artefacts. They have thickness and weight which is a vital part of their value and importance. For hand-struck ancient coins, each has unique characteristics in this regard, despite being mass-produced, and the loss of the third dimension in numismatic studies is significant (Huber-Mörk et al. 2012; Zambanini et al. 2010).

Additionally, while axial lighting is often preferred, there is no standardised protocol of illumination when photographing coins, which may affect the shadows cast onto a coin. Different lighting directions and intensities will influence the highlights and lowlights of the image, potentially exaggerating or diminishing certain elements of the coin (Hess, Macdonald & Valach 2018). The sensitivity of the metallic surface of coins to reflectance, then, makes cross-comparison of coins from different 2D photographic sources limited and research questions, such as whether two coins were minted using the same die, difficult to explore.

The accessibility of coin collections, and the ability to analyse the artefacts in detail and three dimensions, has long been an issue in numismatics. Individual ancient coins represent vitally important artefacts in their own right, offering clues about absolute dates and the relative chronology of strata, as well as hints about connectivity and connections (Evans 2013). They can also be found in collections, both public and private, around the world, although in this context the requirement for many numismatic studies to compare and contrast large numbers of well-preserved examples (e.g. for die studies) means that numismatists must often visit large, established collections to do in-depth research (Metcalf 2012). The impact of the Covid-19 pandemic, and the constraints imposed on both travel and museum opening hours, has further limited access to numismatic collections for researchers and students alike. Thus, even for those with the time and financial means, visiting collections has become difficult, furthering the need for increased digital accessibility. While not yet as contentious as other classes of items (statues, vases, etc.), numismatic collections are not ethically neutral and their continuation, let alone proliferation, should not be taken for granted. Their wide availability and long tradition of collecting has largely obscured the fact that they are, in fact, still plagued by the same issues of provenance, ownership, and association with the illicit antiquities market which taint other categories of artefact (Jarrett et al. 2012). Digitisation of numismatic collections, and making them accessible to researchers, may further bring them into the public sphere so that they can be traced and monitored as other objects are.

The present study developed a successful method for creating 3D digital models of coins using three ancient Roman coins selected from the University of Auckland W. K. Lacey numismatic collection. When developing the method, the primary focus was on circumventing issues surrounding the small size, irregular shape, and reflectance of the coins, and solutions were tested and refined. This paper presents and describes the successful method and outlines the photography equipment, software, and protocol taken to create the 3D digital models. This study continues the wider push, seen particularly in the field of archaeometry (Sheedy & Davis 2020), to both extract more information from ancient coins and make the information we have more widely available. The complexities of digitising small and highly reflective objects have meant that work has progressed slowly in this area while, as discussed above, the need for digitisation has only grown. Here we explore the use of photogrammetry on ancient coins to produce 3D models in a relatively quick and efficient manner as well as outline areas where continued work would be beneficial.

2.0 THE COLLECTION

The coins used in this project are part of the small, teaching collection held in the 'W.K. Lacey Memorial Library', which is part of the Discipline of Classical Studies and Ancient History at the University of Auckland. The collection is largely composed of Roman issues (61 Republican and 61 Imperial), with 29 Greek coins, and a further 25 Italic issues (labelled 'Romano-Campanian'). The coins were acquired in several stages, going back to the middle of the 20th century. The bulk of the collection was donated by Harold Mattingly in the 1950s, as part of a wider set of donations to all the New Zealand Classics Departments active at that time, to encourage the study of ancient numismatics (Ehrhardt 1977, Hamilton 1982–1986). A further donation was made to Auckland in the 1960s by B.F. Harris, although the exact number of coins gifted is not certain, and indeed there is anecdotal evidence to suggest that this period also witnessed some thefts/loses from the collection (Ehrhardt 1993). Ehrhardt provided the first official account of the collection in 1993, as part of a summary of the ancient coin collections across the New Zealand, and listed the W.K. Lacey collection as containing 177 coins – although he also noted that he did not actually see all the coins he listed. As the W.K. Lacey collection was (and is) considered a teaching resource, and is regularly in use and being handled by staff and students, the coins were often distributed across a number of venues and kept as part of other teaching resources for individual classes. The collection was only regularly concatenated in the 1990s, although coins are often loaned for classroom activities. The coins in the collection were formally identified by Robert Loosely in the late 1990s. A small number of additional coins were donated by Anne Gosling in the early 2000s, which represented the remnants of the numismatic collection from the University of Natal (South Africa) as the department there was being reorganised. The collection was formally catalogued, photographed, and analysed in 2019.

3.0 METHODS

3.1 COIN SELECTION

Three coins were selected from the University of Auckland W. K. Lacey numismatic collection for digitisation. The coins were chosen primarily for their applicability to an existing classroom activity and their use in teaching historical analysis, and not with consideration for their suitability for photogrammetry. In 2021, the three coins were used for an exercise on 'Using Ancient Coins as Historical Evidence' in the first-year Ancient History course *ANCIENT 104: Dynasties, Democracy, Empire* at the University of Auckland. Some factors removed coins from the selection process for both the pedagogical exercise and digitisation, most notably a heavily patinated and worn bronze *aes*. All three coins are late Republican/early Imperial, Roman silver denarii (Figure 1). They are made of silver with similar patination, and are of comparable size, but have varied topographical features on the obverse and reverse. All three were graded 'Good (G)' to 'Very Good (VG)' in terms of condition based on adjectival system connected with the 70-point Sheldon Scale (Sheldon 1949), whereby G corresponds to 4–6 and VG to 7–10 while 'Mint' is 60–70. Thus, the coins all feature some surface wearing but all major details are visible (Table 1).

3.2 PHOTOGRAMMETRY SET-UP

Photogrammetry was chosen as the digitisation technique for this study to facilitate an expedient capture of data whilst also accommodating the unique size, shape, and shallow relief of the coins and maintaining high-quality 3D models. The set-up for coin photogrammetry consisted of a light tent surrounded by three LED lights on tripods, a Syrp 8" turntable controlled via Bluetooth, and a custom foam stand with photogrammetry targets printed from Agisoft Metashape 1.8.3 (Agisoft 2022) (Figure 2a). The LED lights were kept at maximum brightness and were placed strategically around the light tent to diffuse the light and therefore minimise light reflected from the coin. The foam stand was placed on a scale for small object photogrammetry developed by Porter (2018) to provide a varied background to aid in the photo alignment process (Porter, Roussel & Soressi 2016). A Canon 800D with a Canon EF 180 mm f/3.5L Macro lens was mounted on a tripod directly in front of the coin. The lens was set at a focal length of f/32 and the ISO set to 400. The Syrp 8" turntable was connected to the camera via a cable, which meant that each photo would be automatically captured at each turn of the turntable. The coin was closely framed in each image and the selection of a macro lens allowed for the detailed capture of the surface of each coin despite their small size. Colour correction was done with an X-Rite Colour Checker Photo Passport 2 and the colour checker was photographed at the start of each rotation. In this method, only two camera angles were captured:

Figure 1 Obverse and reverse images of the coins captured in 2019 as part of the cataloguing process, shot using axial lighting with a Nikon D810 fitted with a 200 mm macro lens. **a)** Coin 28. Struck, silver denarius (113–112 BCE). RRC 292/1., **b)** Coin 74. Struck, silver denarius (47–46 BCE). RRC 458/1., **c)** Coin 86. Struck, silver denarius (29–27 BCE). RIC I (second edition) Augustus 266.

COIN #	DATE	VALUE	NAMES	OBVERSE	REVERSE	INSCRIPTION	MATERIAL	WEIGHT (g)
28	113–112 BCE	Denarius	P. Licinius Nerva	Helmeted head and bust of Roma, r., carrying shield and spear. Crescent above	Three citizens voting in the Comitium. P Nerva (in straight line) above	X before, crescent above, ROMA behind on Obverse and P. NERVA on Reverse	Silver	3.9
74	47–46 BCE	Denarius	G. Julius Caesar	Head of Venus	Aeneas walking and holding palladium and bearing Anchises	CAESAR on Reverse	Silver	4
86	29–27 BCE	Denarius	Augustus (Republican)	Bare head of Augustus to right	IMPCAESAR on architrave of the Curia Julia (Julian Senate House), with porch supported by four short columns	IMPCAESAR on Reverse	Silver	3.7

Table 1 Provenances and descriptions of the coins analysed.

straight on and angled over the coin by approximately 45° (Figure 2b). After each rotation the coin was flipped 180° vertically and the process repeated.

3.3 PHOTOGRAMMETRY METHOD

Two methods of photogrammetry capture were originally utilised to explore data capture expediency and model quality. Whilst the set-up, camera settings, and camera angles remained the same, the first method captured a 90 second video for a full rotation. Video was captured at 1080p and a frame rate of 60 fps. The videos were then imported into Agisoft Metashape 1.8.3 and image stills were automatically captured at a rate of one image per second, with each image ranging from 800 KB to 1.5 MB in size. While this method was promising, the frames extracted from the video were not of high enough quality to allow for alignment, and no models were created with it. We discuss this further below.

The second method, and ultimately the final method chosen, required the capture of 25 RAW images for each rotation, with the images ranging from 40 MB to 60 MB in size (Figure 2b). Two full rotations were done for each camera angle, allowing the coin to be flipped vertically and for all surfaces of the coin to be captured. This process took approximately 180 seconds per rotation and resulted in 100 photos in total per coin. The use of the Syrp 8" turntable somewhat automated this process, whereby the turntable was programmed to stop for each of the 25 photos and the photo capture was automatically triggered. While this method was more time consuming, the image quality was significantly higher than the images extracted from the video. Given that each rotation for the photography only took 90 seconds longer for data capture than the video capture, it is still a relatively efficient and automatic acquisition.

The 3D models were constructed using Agisoft Metashape 1.8.3 with a method adapted from Emmitt, Mackrell and Armstrong (2021). For each coin, the photos were imported and subsequently aligned with the quality at 'high' and the tie points were then edited. It was found that an 'ultra high' alignment quality was overly aggressive and resulted in less photos aligned. After alignment, the editing parameters remained relatively consistent across each coin (Reprojection Error: 0.2 px; Reconstruction uncertainty: 15 px; Projection accuracy: 5 px). From the resulting tie points, a model was created using depth maps.

The model of each side was used to mask the images used in the reconstruction. Automatic alignment did not produce a correct alignment, which may be related to the reflection on the edges of the coins. To merge the two sides, they were aligned manually by the addition of markers on each side of the coin and aligning the models. The two sets of tie points were merged and a final model created using depth maps. A texture was created for the model and, using marks on the original photos, the models scaled.

The resulting models are presented in Figure 3. The 3D models are also available at Emmitt, Morris and Armstrong 2022a.

4.0 CHALLENGES AND CONSIDERATIONS

The challenging and varied shape of the coins, as well as issues surrounding reflectance, required a similar but ultimately unique methodology compared to those undertaken by the team on other artefact types in past studies on 3D modelling (Emmitt, Mackrell and Armstrong 2021; Emmitt, McAlister and Armstrong 2021; Emmitt et al. 2021). Coins pose several optical

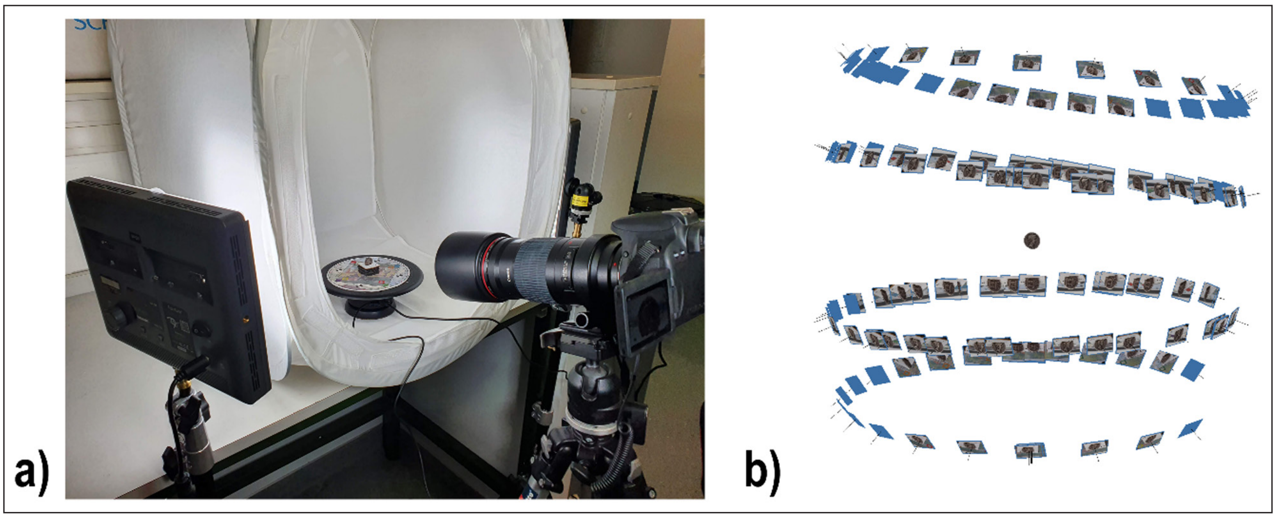

Figure 2 Data collection. **a)** Data collection area with lights, turntable, and camera. **b)** Positions of the angles captured. Both sides of the model are represented.

Figure 3 Obverse and reverse views of the coins taken from the 3D models. **a)** Coin 28 (Emmitt, Morris and Armstrong 2022b). **b)** Coin 74 (Emmitt, Morris and Armstrong 2022c). **c)** Coin 86 (Emmitt, Morris and Armstrong 2022d).

challenges compared to other artefacts. Ancient, and particularly Roman, coins are often small with shallow relief and varied surface properties. Perhaps their most distinguishing characteristic is that they are reflective, either as they were preserved or through modern cleaning, making it difficult to capture consistent images across a full rotation due to changes in the reflection of light from the coin. In particular, this was an issue for the edges of the coins and curved elements on the raised relief on the faces. This is seen in the confidence measures of the models, where lower values show areas where there was less overlap between photos, in contrast with higher values that show more overlap between photos (Figure 4).

The reflectance on the edges and some of the faces is likely the reason behind the inability of the software to automatically align the two sides of the coin. Coin 86 was particularly affected by this, which is also seen in the relatively lower confidence in the final model compared to the other two (Figure 4). This is also seen on the obverse of coin 28 where the helmet of the goddess Roma and the area that surrounds it has a lower confidence than elsewhere. The helmet is a smoother area with less features than the rest of the coin, due to increased wear.

Reflectance is also likely why the video data were not sufficient for a successful alignment. The relative low-quality of the extracted frames was an issue, but also the fact that the frames were taken from an object in

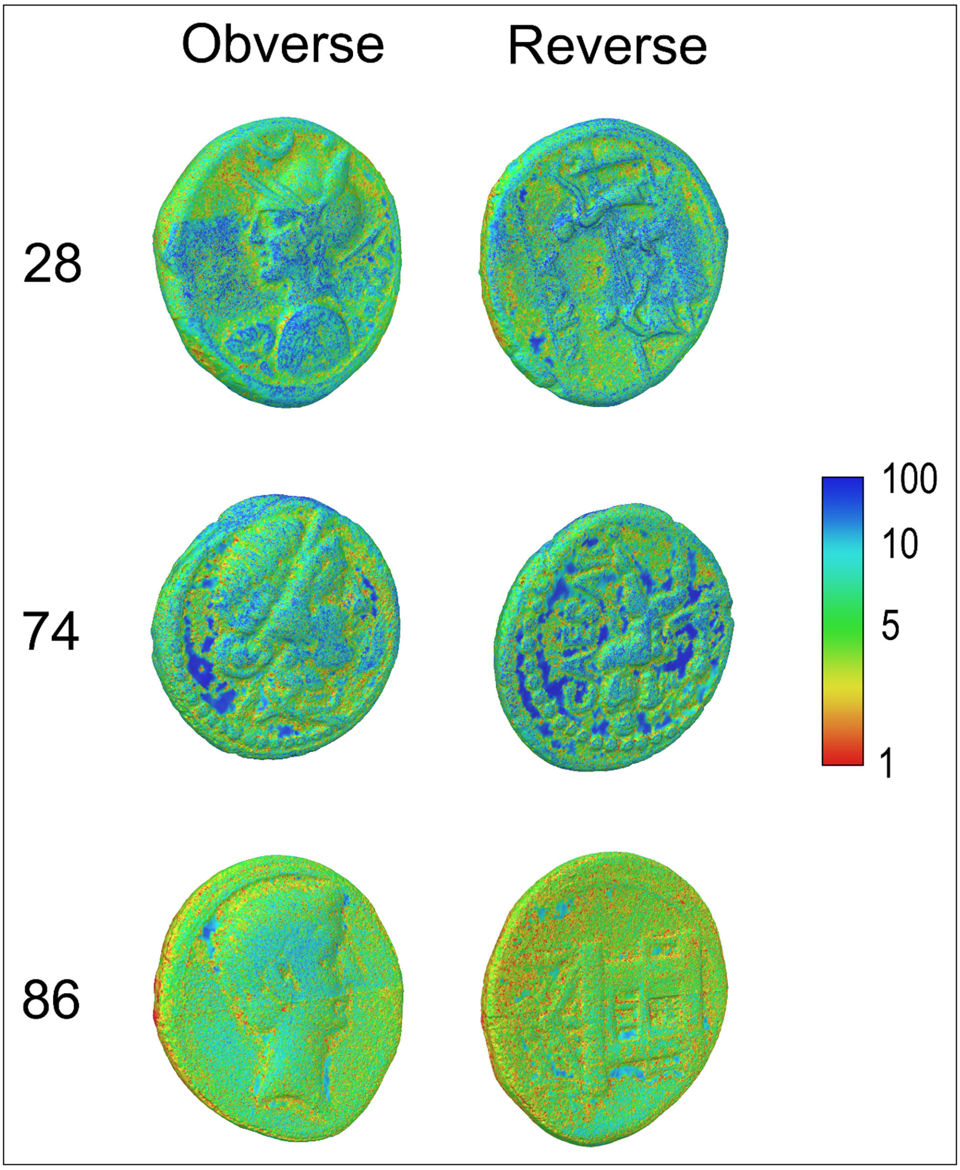

Figure 4 Confidence measures for the final models of the coins. Coins are presented in isometric and with the obverse side oriented up.

motion, which created some, albeit minute, motion blur. Conversely, this is why the comparatively high-resolution images *did* work, as they were taken on a still object at a much higher resolution.

Several iterations of a coin-specific base were trialled for this project. Due to the coins' small size, curved shape, and thinness, the process required a base that both held each coin still and kept them on an exact, vertical axis during rotation. A non-vertical axis would result in colour discrepancies on the final texture due to differences in shadow. Additionally, the shape of the coin required a base that securely held the coin vertical, while also exposing at least 3/4th of the obverse and reverse of the coin to assist with photograph alignment in Agisoft Metashape (1.8.0) (Agisoft 2022).

In the end, we constructed a foam base with a rectangular cut-out to fit a coin, with custom targets printed from Agisoft Metashape. Two target placements were trialled, with small targets surrounding the base and small targets surrounding the coin (Figures 2a, 5), allowing for a close crop and thus a higher quality image of the coin. The targets, while useful for the manual scaling of the object, were not useful for aligning the photos as they could not be printed at a high enough resolution to make them clear enough for detection for the software (the central dot needs to be visible, which was smaller than could be printed). The base chosen for the final method, therefore, prioritised the quality of the macro photography by stabilising the coin in a vertical position and allowing for a close crop of the coin within each image.

5.0 DISCUSSION

This study has developed and demonstrated a method for creating high-quality 3D digital models of ancient coins in an expedient manner. From provisional experimentation, it is evident that 3D digital models of ancient coins can provide some intermediary between the traditional approach of using 2D images and the physical handling of coins. They provide an opportunity for detailed inspection while maintaining a higher degree of dimension than 2D images. Issues with reflectance were largely circumvented by capturing multiple images of the coin at two angles using the same lighting direction and closely cropped, high-quality macrophotography. The result was three digital models that were largely representative of the physical coin in both relief and colour – enough so that the resulting models could be examined with raking light in software such as Meshlab 2022.02 (Meshlab 2022) (Figure 6). Importantly, the present methodology captured, with high accuracy, the unique topography of the coin edges – an aspect of the coin that is difficult to capture in a 2D image.

The aim of this study was to develop an expedient yet effective method for the capture of 3D ancient coin models. Unlike other ancient artefacts, coins are difficult to photograph due to their shape and size, and therefore have not received the same attention as other artefacts in the digitisation sphere. Traditionally, 2D images and written descriptions of coins have been the primary form of numismatics record keeping. Such records from the University of Auckland numismatic collection were previously used in the first-year Ancient History course

Figure 5 Image captured for photogrammetry reconstruction of the coin 28 obverse.

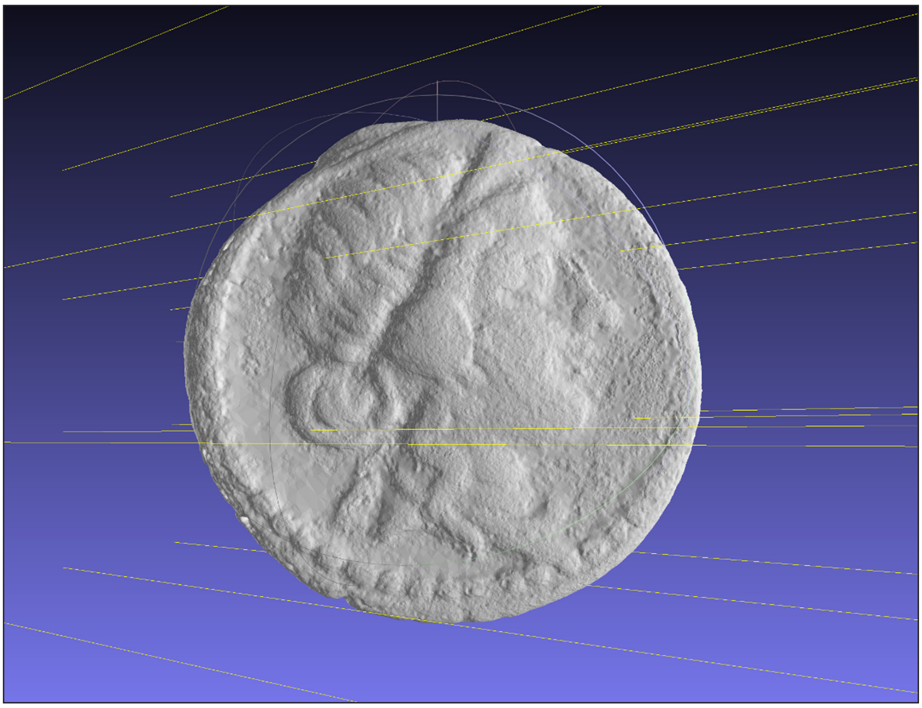

Figure 6 Example of coin 74 under simulated raking light in MeshLab 2022.02. Yellow lines indicate the direction of light.

ANCIENT 104: Dynasties, Democracy, Empire in addition to students interacting with the coins themselves. While efforts towards digitisation were already being considered, remote learning in 2020 and 2021, due to the Covid-19 pandemic, necessitated an alternate approach to teaching in lieu of students not being able to access the coins directly. The use of 2D images alone provided limited opportunity for comparative analysis of the coins. This study sought to build 3D models of all three Roman Republican coins to use pedagogically while also developing a unique methodology that accounted for the peculiarities and challenges of coins as a photographic subject. Details of the pedagogical work (conducted under the aegis of the University of Auckland Human Participants Ethics Committee, reference number UAHPEC21648) will be outlined in a subsequent study.

Of particular interest for the photogrammetry was the efficiency of image capture and the time needed to create a 3D model for each coin. Both the feasibility and desirability of the 3D capture of ancient coins has been established, at least in principle, for over a decade (Zambanini et al. 2010). The problem has long been the cost/benefit analysis. Creating high-quality 3D models of coins is difficult due to their small size and reflective properties, while excellent quality 2D records are relatively cheap and simple to produce. Given the tremendous time and effort it takes to create a single 3D model of a coin, which is often not as sharp or detailed as 2D images when considering only the obverse and reverse, this medium has typically been relegated to the category of 'interesting curiosities'. For this reason, both photo and video capture were trialled. Ultimately, with an automatic turntable to assist with data capture, photographs were not much slower than video, with a more viable and superior result.

The expediency of the method presented, and the resulting quality of the 3D models created, provides a promising glimpse into the possibilities and use of these models for research, accessibility, and pedagogy. 3D models not only allow a more detailed inspection of coins than 2D images, but they also provide further opportunity for the accessibility of both public and private collections. A wider audience – both students and researchers alike – can access, interpret, and compare data from collections across the world that would otherwise be inaccessible. As this study has demonstrated, it is possible to create digitised 3D models of ancient coins in a relatively expedient manner at a high enough quality to analyse fine details on the coin, such as inscriptions and distinct die marks. Large qualitative studies can thus be undertaken using 3D models, such as automatically detecting which coins were cast by the same die, which opens a new expanse of research opportunities. This information can be further supplemented by high-quality 2D images – one medium need not replace the other. This level of accessibility has the potential to open up new research endeavours that have previously been limited or, due to financial or logistical reasons, unachievable. Despite their varied and often difficult shapes and sizes, ancient coins can and should be included in the wider push for increased digitisation of ancient artefacts.

6.0 CONCLUSIONS

While the digitisation of ancient artefacts for research purposes continues to garner attention in a range of contexts, from academic study to museums and classrooms, digitisation of ancient coins has remained limited due to challenges related to their small size, curvature, and high level of reflectance. The present study developed a method for digitising ancient coins and the results have been presented here. Using photogrammetry, this study created 3D digital models of three Roman Republican coins from the University of Auckland's W. K. Lacey numismatic collection for student use. Several solutions for circumventing the challenging aspects of capturing coins were found and refined. Importantly, the method presented here prioritised the high-resolution of each image by utilising macrophotography, a custom coin base that kept the coin consistently vertical during each rotation, diffused lighting, and closely cropped images, which resulted in high-quality 3D models that were created in a relatively expedient manner. The set-up and equipment used for this study has been described and the method outlined.

The benefits of 3D modelling ancient coins are clear and generally accepted. The issues which have stopped their widespread digitisation are their small size, large number (and the large number needed for either study or use), reflectance, and curvature. Through the techniques given, we have highlighted how the small size and reflective characteristics can be accounted for and have offered a method which would allow for the relatively quick digitisation of a large collection once the initial set up was created. Further developments in photogrammetry capture will likely continue to mitigate these issues, and when they do it will enable the further scaling of this method to create 3D models of more coins. With a large enough sample, a range of potential applications become viable, such as the automatic assignment of die, for example. Like all 3D models of artefacts, they will never fully replace the original in terms of meaning and study, but similar models can still advance the wider field of study in important ways.

DATA ACCESSIBILITY STATEMENT

The models presented in this paper are available at: Emmitt, J., Morris, G., and Armstrong, J. 2022a. Roman coin models published in "Depth and Dimension: Exploring the Problems and Potential of Photogrammetric Models for Ancient Coins". Figshare DOI: 10.17608/k6.auckland.19790689.

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COMPETING INTERESTS

The authors have no competing interests to declare.

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