Journal of the American Institute for Conservation

REFLECTED INFRARED AND 3D IMAGING FOR OBJECT DOCUMENTATION

--Manuscript Draft--

Manuscript Number:	JAC231R2
Full Title:	REFLECTED INFRARED AND 3D IMAGING FOR OBJECT DOCUMENTATION
Article Type:	Original Research Paper
Keywords:	infrared imaging, 3D imaging, photogrammetry, white light scanning, reflected infrared imaging
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Abstract:	Imaging techniques inform the conservation, research, and understanding of museum collections. Two types of imaging techniques were examined in this study: infrared and 3D imaging. Reflected infrared imaging is well established as an investigative tool for conservation providing information about condition, materials, and manufacture beyond visible light documentation. Reflected infrared imaging results in 2D images, which are limited in how they represent three-dimensional objects. 3D imaging techniques, such as white light scanning and photogrammetry, extend the possibilities of digitization by recording the geometry and texture of an object. Reflected infrared imaging, photogrammetry, and white light scanning were used to document six objects from the Freud Museum and the Smithsonian National Museum of the American Indian. The present study provides examples of reflected IR imaging for enhanced detection of features of three-dimensional cultural heritage objects; discusses the potential of integrating reflected IR and 3D imaging to more fully document features of three-dimensional objects; and investigates two 3D imaging techniques, white light scanning and photogrammetry. The study assesses the two 3D imaging techniques, one more expensive and the other more accessible, to discover whether there is a significant difference in performance for the purpose of resolving the details recorded by reflected IR imaging.
Additional Information:	
Question	**Response**
Author Comments:	July 2015 Thank you so much for accepting the paper. I have made the changes the editors and the reviewers have included. I have not provided responses as I agree with the suggestions and have made the changes accordingly. I will provide a list of changes that includes the reviewers' comments followed by the changes made. Thank you, Keats December 2016 Over the past several months I have been working to revise this paper based on the reviewers comments and feedback from my supervisors and advisors. Revisions have

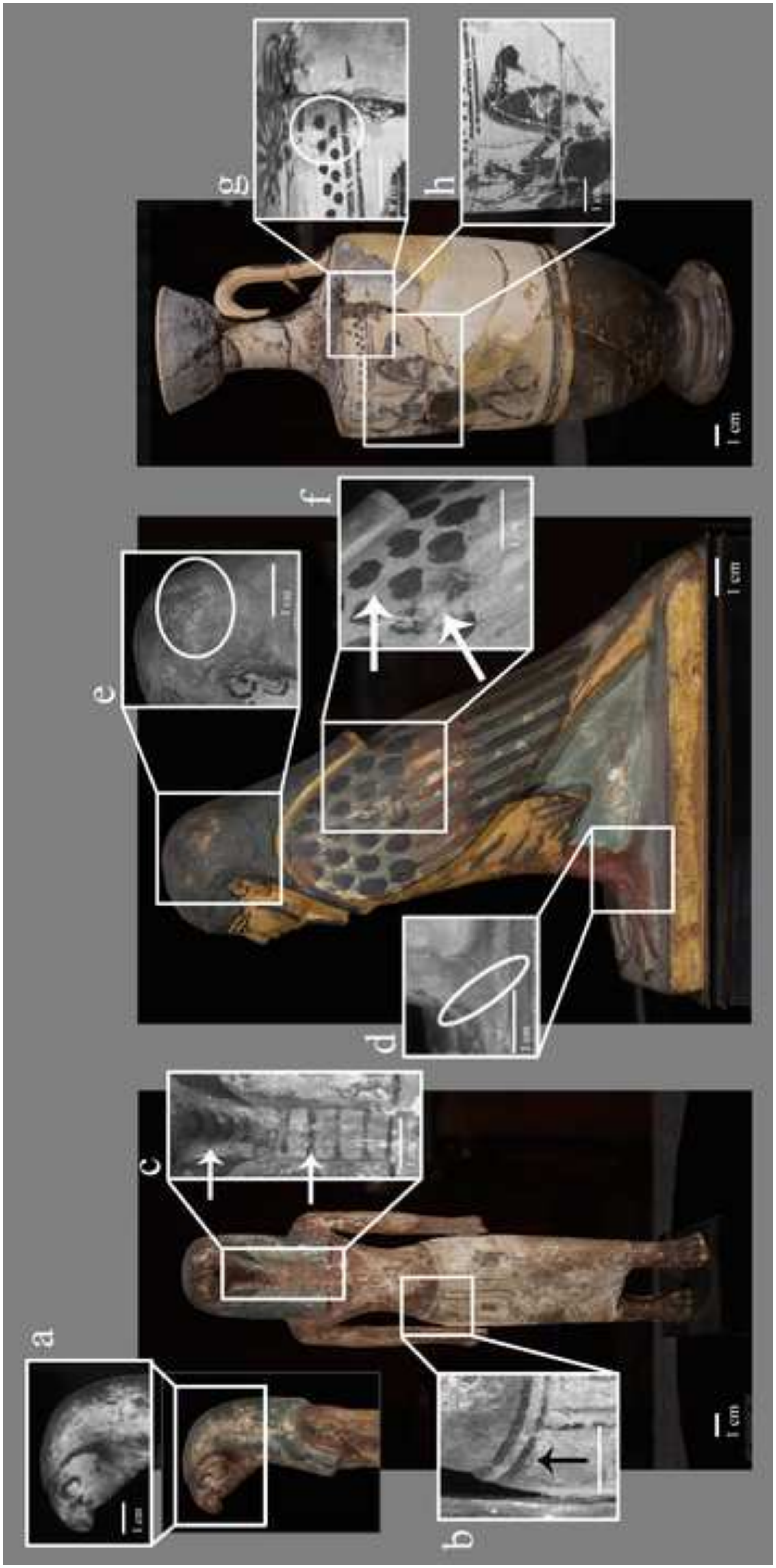
	addressed the larger issues of not presenting reflected IR imaging as a new technique for documenting 3D objects, providing a wider context of 3D in conservation including mentioning micro-CT scanning and 3D digital microscopy, and including additional justification for selection of equipment. I have also included brief responses for the Reviewers specific feedback. Thank you, Keats
Response to Reviewers:	
Funding Information:	

Color figure (figure 1)

Click here to download Color figure Fig1_6_objects_FM_NMAI.jpg

Color figure (figure 2)

Click here to download Color figure Fig2_FM_IR-VIS_results.jpg



Color figure (figure 3)

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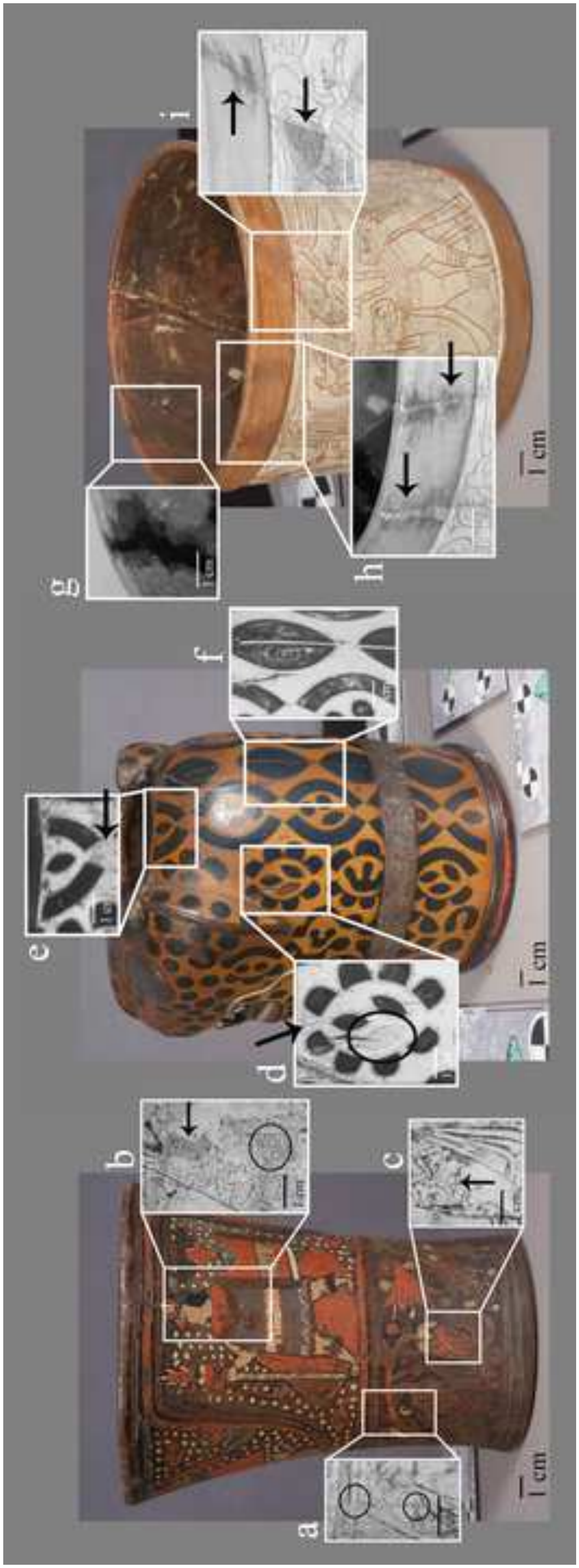

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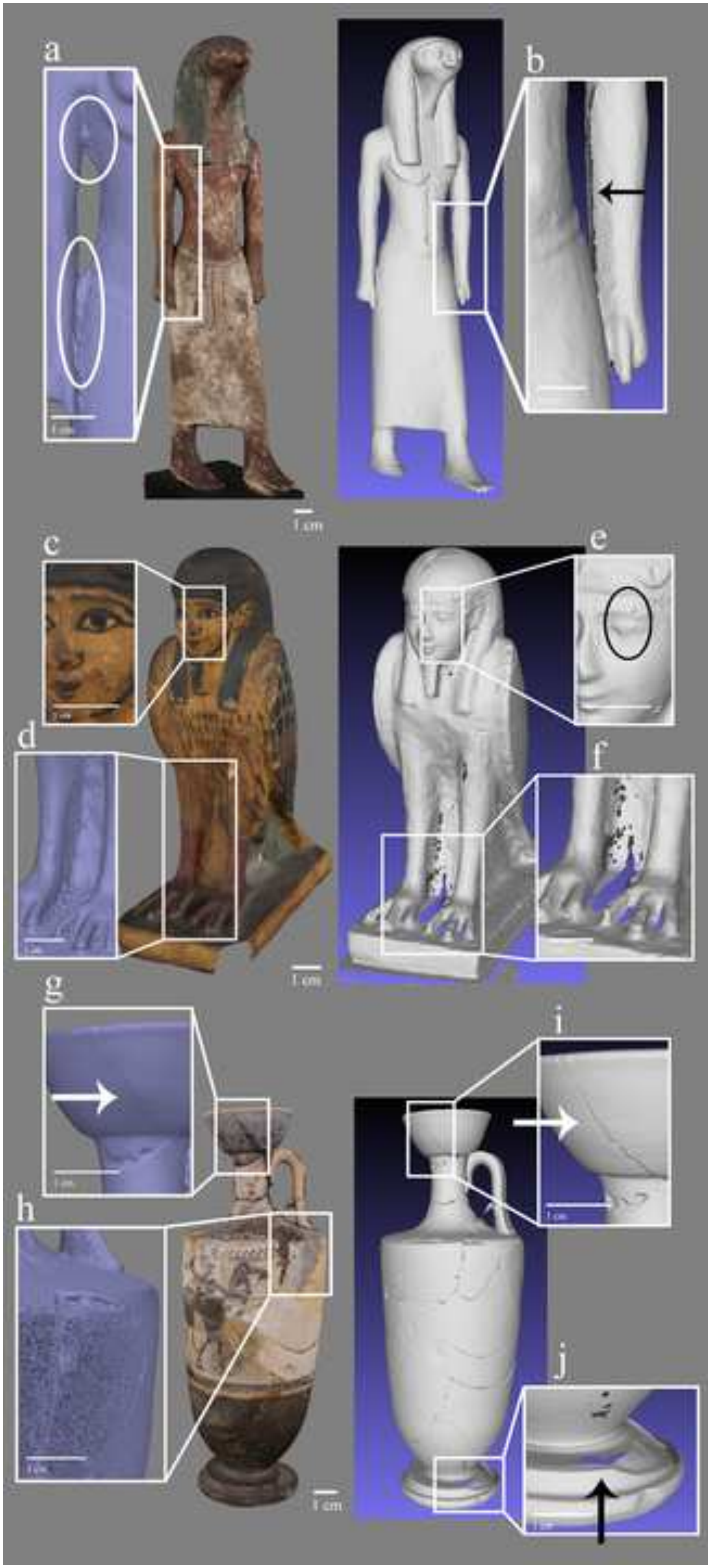

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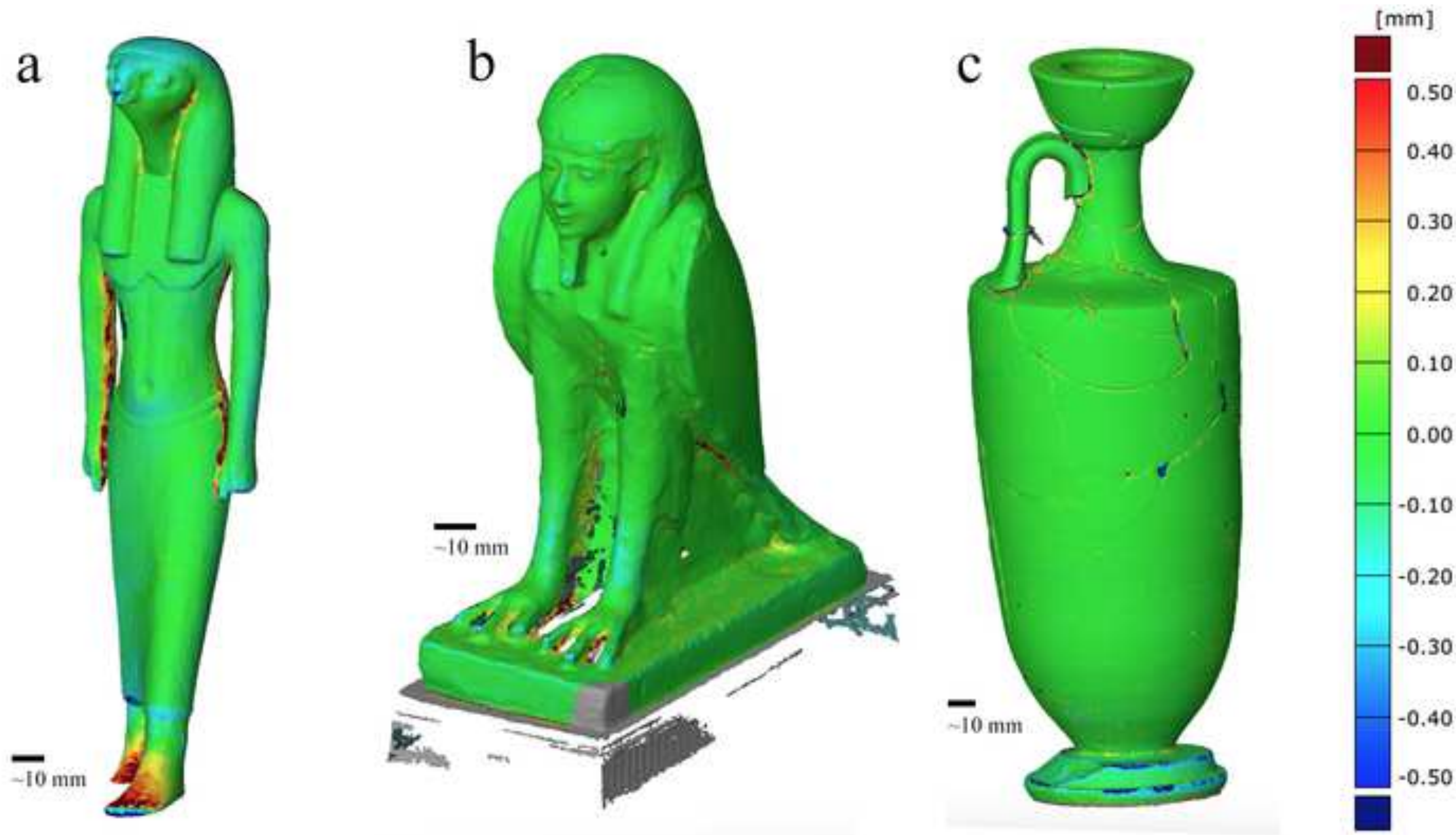

Reflected Infrared and 3D Imaging for Object Documentation

Imaging techniques inform the conservation, research, and understanding of museum collections. Two types of imaging techniques were examined in this study: infrared and 3D imaging. Reflected infrared imaging is well established as an investigative tool for conservation providing information about condition, materials, and manufacture beyond visible light documentation. Reflected infrared imaging results in 2D images, which are limited in how they represent three-dimensional objects. 3D imaging techniques, such as white light scanning and photogrammetry, extend the possibilities of digitization by recording the geometry and texture of an object. Reflected infrared imaging, photogrammetry, and white light scanning were used to document six objects from the Freud Museum and the Smithsonian National Museum of the American Indian. The present study provides examples of reflected IR imaging for enhanced detection of features of three-dimensional cultural heritage objects; discusses the potential of integrating reflected IR and 3D imaging to more fully document features of three-dimensional objects; and investigates two 3D imaging techniques, white light scanning and photogrammetry. The study assesses the two 3D imaging techniques, one more expensive and the other more accessible, to discover whether there is a significant difference in performance for the purpose of resolving the details recorded by reflected IR imaging.

Keywords: infrared imaging, 3D imaging, photogrammetry, white light scanning, reflected infrared imaging

1. Introduction

The emerging field of heritage science combines the humanities and the physical sciences to address the needs of the arts, archaeology, and natural science sectors through management, conservation, interpretation, and digitization. Digitization, imaging and documentation, for research and conservation is a pillar of this field. It documents condition, informs care, and increases knowledge of heritage objects when well designed and executed. Digital imaging techniques are generally non-invasive and portable, attributes that are priorities when working with heritage objects. Among these techniques, reflected infrared (IR) imaging allows the enhanced detection of features as seen in applications for paper and paintings conservation to detect underdrawings, observe compositional changes, differentiate materials, and enhance obscured or faded features (Warda et al. 2011). This information about condition, materials, and manufacture of objects can provide observations beyond what is documented in the visible range for two-dimensional and three-dimensional objects. However, features of three-dimensional objects are not fully recorded with 2D images. 3D imaging can provide a better representation of three-dimensional objects by documenting the geometry and texture, or color, of cultural heritage objects. 3D imaging techniques including white light scanning and photogrammetry have been used for cultural heritage documentation for applications including research, conservation, replication, and exhibition.

1.1 Reflected IR Imaging

IR radiation has been used for cultural heritage documentation since the 1930s when film sensitive to near infrared (NIR) radiation (up to ~ 900 nm) became available (Warda et al. 2011). IR imaging records the varying reflection, transmission, and absorption of IR radiation by the materials present in an object. Following the terminology outlined in Warda et al. (2011), *reflected IR* will refer to imaging that uses wavelengths in the NIR region (700-1000 nm) and corresponds with the sensitivity of IR films and digital cameras with silicon detectors, and *IR reflectography (IRR)* will refer to imaging that uses wavelengths in the short-wave infrared (SWIR) region (1000-2500 nm) and requires specialized sensors (Warda et al. 2011 and Fischer and Kakoulli 2006).

Reflected IR imaging and IRR are established investigation tools for painting and paper conservation for detection of features beyond visible light documentation. Early reflected IR imaging included investigating the artist's technique to reveal guide lines (Keck 1941) and to provide clearer documentation of a painting obscured by aging varnish (Rawlins 1938). Van Asperen de Boer (1969) extended the sensitivity of reflected IR imaging from NIR to SWIR by introducing the use of the Vidicon system as a tool for detecting underdrawings in paintings. Mairinger (2004) included applications of reflected IR examinations for graphic arts (drawings, prints and illuminated manuscripts) and paintings to increase legibility of manuscripts, differentiate inks and pigments, detect compositional changes, and reveal underdrawings. As digital camera technology has evolved, IR imaging continues to develop. Falco (2009) presented the use of a modified digital camera for documenting art works in the NIR with an example of revealing underdrawings in a painting. Additional examples of conservation applications for paper and paintings include Arslanoglu et al. (2013) who used IRR to complement X-ray radiography of paintings in the investigation of working methods and materials, and Gavrilov et al. (2013) who compared NIR, SWIR, and thermographic imaging for paintings inspection to look at working methods, changes in composition, and structural defects. These references reflect the history and development of reflected IR imaging for paintings and paper conservation and represent only a few of the many studies available.

In addition to the wide use of reflected IR imaging for two-dimensional items, a few published studies provide examples for reflected IR documentation of three-dimensional objects. Moss (1954) reported imaging repairs on a lustre jug, and Gibson (1978) referenced studies of metals, a wooden object, stained glass, pottery fragments, and painted elements of archaeological sites. Mansfield et al. (2002) and Warda et al.

(2011) suggested applications beyond paintings and paper, but did not provide specific details. Falco (2009) included a single example, a set of Japanese armor, where the technique was used for material differentiation.

The current availability of modified consumer DSLRs for reflected IR imaging provide the option of higher spatial resolution cameras in comparison to the specialized cameras with SWIR sensitivity that are more expensive and tend to have a low spatial resolution. Modified DSLR cameras provide a lower cost option for conservation labs to conduct IR imaging. Additionally, these systems provide resulting 2D images with a high resolution and more potential to record small details. However, 2D imaging techniques, both visible and IR, provide only a limited representation of three-dimensional objects.

1.2 3D Imaging

3D imaging is used for cultural heritage documentation to record the surface geometry and in some cases texture of an object producing virtual and physical 3D models. 3D imaging allows digitization to extend beyond the limitations of 2D object documentation to monitor dimensional change, virtually reconstruct an object, reduce handling and grant access, create custom mounts or repairs, and produce replicas (Hess 2015). Techniques include range-based techniques like laser and white light scanning and image-based techniques like photogrammetry (see, Remondino 2011c). Other 3D imaging techniques such as computed tomography (CT) scanning and micro-CT scanning use x-rays to record the shape and volume of an object, and 3D digital microscopy records geometry at the micro-scale. Reviews of 3D imaging techniques for cultural heritage applications include Wachowiak and Karas (2009), Engel (2011), and Remondino (2011a, 2011b, 2011c). A variety of 3D imaging techniques have been used for conservation applications, for example, white light scanning to create a physical copy and virtually recreating a missing piece (Wachowiak, Karas, and Baltrusch 2009); laser scanning for virtual reconstruction and custom support production (Arbace et al. 2013); and laser scanning for monitoring internal movement (Garland, Bernstein and Rogers 2015) and dimensional stability (Hess et al. 2015). These are only a few of many publications on 3D imaging for cultural heritage.

The present study focused on assessing two 3D imaging techniques that have been used for conservation applications, white light scanning as a more expensive and specialized option, and photogrammetry as a lower cost and more accessible technique using similar equipment to what was used for reflected IR imaging. White light scanning is a range-based technique that involves the projection of light patterns onto an object and the recording of the pattern deformation to produce a 3D model of an object. It is a portable and accurate 3D imaging technique with good texture acquisition and useful for small-scale objects (Pratikakis, Koutsoudis, and Savelonas 2013). Photogrammetry is an image-based technique where surface geometry of an object can be estimated from at least two overlapping images. The term photogrammetry encompasses several distinct techniques using different algorithms and calibration methods. Remondino et al. (2012) discusses how the photogrammetry community prioritized *accuracy* and *reliability* for applications in mapping, documentation and monitoring, while the computer vision community prioritized *automation* for applications in robotics and inspection (Remondino et al. 2012, 41). An example of an automated, image-based method developed by computer vision is Structure from Motion (SfM), a self-calibration approach that is widely used in cultural heritage documentation.

1.3 Assessing 3D Imaging Techniques

As 3D imaging techniques are becoming more widely used in cultural heritage, many case studies and comparative studies have been published. Engel (2011) described 3D technologies for natural history collections; Mathys, Brecko, and Semal (2013) compared five 3D imaging techniques; Koutsoudis, Vidmar, and Arnaoutoglou (2013) evaluated the performance of photogrammetry of a low-feature artifact compared to that of laser scanning; Mathys et al. (2013) assessed low cost techniques for field archaeology; and Abate et al. (2014) investigated 3D techniques for paintings. These publications provide examples of parameters that have been used to assess 3D imaging techniques including accuracy, shape discrepancies, and resolution. Bryan, Blake, and Bedford (2009) defined accuracy as “the closeness between measurements and their true values. The closer a measurement is to its true value the more accurate it is” (20). Shape discrepancies, or surface deviations, have been used to assess the accuracy of a technique compared to true values or to another 3D imaging technique (Koutsoudis, Vidmar, and Arnaoutoglou 2013; Mathys, Brecko, and Semal 2013) and to measure the difference between two aligned models.

Sampling resolution is used as a parameter for assessing quality and output of imaging techniques (Remondino et al. 2013). The resolution of range-based methods is defined by the specifications and performance of the device as provided by the manufacturer (Remondino et al. 2013). The resolution of image-based methods can be estimated as the ground sampling density (GSD) calculated from the object to camera distance, the focal length of the lens, and the pixel size of the camera (see, Andrews, Bedford, and Bryan 2015). Understanding and evaluating the resolution for a technique requires knowing the size of the smallest feature that needs to be resolved for specific uses and the users. According to MacDonald (2010), the smallest feature size for most heritage materials would be in the range of 0.02-0.075 mm. The number of pixels (px) per mm, or the sampling rate, for digitization should be at least twice the value of the smallest feature (mm) that needs to be resolved (MacDonald 2010). Resolving features in the range of 0.02-0.075 mm would require a sampling rate of 27-100 px/mm for digitization. MacDonald (2010) suggested a standard digitization resolution of 50 px/mm to ensure that the details of 0.04 mm are resolved.

1.4 Experimental Design

Reflected IR imaging, photogrammetry, and white light scanning were used to document six objects (fig. 1) two Egyptian painted wood figures and a Greek ceramic vessel from the Freud Museum in London and two wood qeros and a ceramic vessel from the Smithsonian National Museum of the American Indian (NMAI) in Washington, DC. The present study provides examples of reflected IR imaging for enhanced detection of features of three-dimensional cultural heritage objects; discusses the potential of integrating reflected IR and 3D imaging to more fully document features of three-dimensional objects; and investigates two 3D imaging techniques, white light scanning and photogrammetry. The main objective is to compare the two techniques, one more expensive and the other more accessible, to discover whether there is a significant difference in performance for the purpose of resolving the details recorded by reflected IR imaging.

In the current study, reflected IR imaging was conducted with a modified DSLR camera. A similar setup for photogrammetry was used to maintain consistency for comparison between IR and visible in addition to the consideration of future research acquiring integrated data. A high performance lens was used for sharp results and to minimize focus shift between visible and IR (Warda et al. 2011, 138). The Peca 906 longpass filter, comparable to the Kodak Wratten 87A filter, was selected as it cuts off shorter IR wavelengths and could maximize the transparency of some materials. A Breuckmann SmartSCAN, used in the present study, is often utilized for industrial inspection, quality control, and reverse engineering, which all require high accuracy and precision. These systems also tend to be user-friendly with a simple calibration process and accurate color capture. The SfM method of photogrammetry was selected for the present study as an inexpensive, portable, and accessible 3D imaging technique (Abate et al. 2014; Nicolae et al. 2014). The method is based on standard camera equipment, and some of the software solutions are available as freeware or are more affordable than some proprietary 3D scanning or analytical software.

2. Case Studies

2.1 Freud Museum (London, UK)

The Freud Museum (Maresfield Gardens, London, UK) is located in the family home of psychoanalyst Sigmund Freud where he lived the last year of his life. His daughter, Anna Freud, continued to live in the family home until her death in the 1980s when the house was converted to a museum. The museum now maintains and exhibits Freud's libraries, archives, and his collection of nearly 2000 Egyptian, Roman, Greek, and Oriental antiquities. Acquisition in February and March 2015 included twenty collection objects imaged with visible light imaging, reflected IR imaging, photogrammetry, and white light scanning. Three objects, (1) the *Falcon-Headed Figure* (LDFRD 3124)*;* (2) the *Human Headed Ba-Bird* (LDFRD 3286); and (3) the *Lekythos* (LDFRD 3702) are discussed in this paper.

The *Falcon-Headed Figure* (fig. 1a) is considered to be a 19th century forgery of an Egyptian antiquity (FM Collections Catalog). The figure, a human body with a head shaped like a bird, was carved from wood and decorated with gesso and paint. It is thought to be a representation of Horus, the god of the sky and protector of the pharaoh (Gamwell and Wells 1989, 58 cited in FM Collections Catalog).

The *Human Headed Ba-Bird* (fig. 1b) is from the Egyptian Ptolemaic Period (332-30 B.C.) (FM Collections Catalog). The object, a bird body with a human head, was carved from wood and decorated with gesso and paint. It is thought to have been a part of a rounded wooden funeral stele and representative of the "ba", which along with the body and the life force were the three elements that a person was divided into at death (Gamwell and Wells 1989, 72 cited in FM Collections Catalog). The "ba" can take the form of a bird to return to the land of the living.

The *Lekythos* (fig. 1c) is from 5th century BC Greece (FM Collections Catalog). The catalog lists the object as a 'black figure' vessel depicting two warriors walking beside their horses. The *Lekythos* was reconstructed from many pieces, and parts of the decorations, warriors, horses, and the design, have been obscured by the reconstruction materials, fading, and wear.

2.2 Smithsonian National Museum of the American Indian (Washington, DC)

The Smithsonian National Museum of the American Indian (NMAI) holds one of the world's largest collections of Native artifacts from the Western Hemisphere. Founded by George Gustav Heye, the Museum of the American Indian/Heye Foundation acquired the majority of the items in the collection from 1903-1957 with objects of "artistic, historic, literary, and scientific interest" that were to become the collections for "a museum for the collection, preservation, study, and exhibition of all things connected with the anthropology of the aboriginal people" of the Western Hemisphere as stated in the 1916 trust agreement (NMAI Website). Three collections objects were examined for this study in June 2015 with visible light imaging, reflected IR imaging, and photogrammetry of three collection objects, (1) *Inka Qero* (NMAI 16/3605); (2) *Inka Qero (Jaguar head)* (NMAI 10/5860); and (3) *Vessel* (NMAI 23/9575).

The *Inka Qero* is an Andean qero, or ceremonial drinking vessel, manufactured 1550-1800 most likely in the Cusco region of Peru (fig. 1d) (NMAI Collections database record for 16/3605, accessed August 2, 2015). The NMAI collection of qeros has been investigated for the identification of materials and manufacture techniques in a long-term technical study (Kaplan et al. 2012; Newman, Kaplan, Derrick 2015). The form of this wooden vessel is typical for most qeros: an hourglass profile with the rim larger than base. This vessel is decorated in typical Colonial Inka style: incised lines and carved recessed motifs inlaid with pigmented resin to create figures and designs. There are depictions of a male and a female human figure on opposing sides of the vessel, two feline heads with rainbows springing from two feline heads, and design elements of flora, fauna, and geometric patterns. Craquelure patterns typical of this resin are observed in the polychromed areas; the incising and carving features are more visible in areas of loss.

The *Inka Qero (Jaguar head)* is an Andean ceremonial drinking vessel manufactured circa 1700 most likely in the highlands of Peru (fig. 1e) (NMAI Collections database record for 10/5860, accessed August 2, 2015). This wooden vessel in the shape of a jaguar head is an unusual but not unique form and the decoration, again, is atypical. This vessel includes pelage-patterned spots for the jaguar's fur, silver discs for the eyes, a ferrous metal band around the neck, and brass serpents as whiskers. Some of the spots in the pelage patterns do not contain any coloration, which may indicate surface loss.

The *Vessel* is listed in the catalog as an "incised clay cylindrical bowl with a flat bottom" from Mexico and described as a "Yucatan bowl" with an unknown manufacture date (fig. 1f) (NMAI Collections database record for 23/9575, accessed August 2, 2015). This type of object, known as a Maya cylinder vessel, is typically made of ceramic. However, NMAI Curator Dr. Antonio Curet and NMAI Conservator Emily Kaplan (pers. comm.) noted that it is of suspicious authenticity due to its appearance under ultraviolet-induced fluorescence and its extraordinarily light weight suggesting it is made of plaster. Imaging was carried out to try to determine whether any part of the vessel was actually original ceramic. Cracks throughout the object are visible and suggest a past treatment to restore the vessel from a number of fragments, perhaps as part of the process of creating a fake.

3. Methods

3.1 Imaging Techniques

Reflected IR imaging was performed using a modified Canon 5D Mark II with a Coastal Optics 60 mm macro UV-VIS-IR APO lens. Modifications included the removal of the IR-cut filter and the color filter array with the result that it is sensitive to IR radiation up to about 1000 nm and acquires only monochrome images. A longpass Peca 906 filter on the lens was used to restrict the recorded radiation to the NIR region, cutting off wavelengths below about 950 nm. The objects were illuminated with the two Lowel ViP Pro-lights with tungsten halogen lamps.

Photogrammetry was performed using a Canon 5D Mark II camera with a Coastal Optics 60 mm UV-VIS-IR APO macro lens. The objects were illuminated with the same lights as described above. The camera was mounted on a tripod with the object centered on a manual turntable. The turntable allowed for the object to be rotated while maintaining a constant working distance from camera to object. The image sets included multiple positions made up of views documenting a full rotation of the object. Agisoft Photoscan Pro software was used for processing the images into 3D models using a workflow provided by Cultural Heritage Imaging and the US Bureau of Land Management.

White light scanning was performed using the Breuckmann SmartSCAN with two 5-megapixel cameras, 300 mm lenses, and an automated Breuckmann turntable. The data was acquired and processed using the proprietary Breuckmann 3D software, OptoCAT 2014. The white light scanning was conducted in the Freud Museum during open hours, so control over the ambient light was not possible and texture information was not acquired. A 3D scanner was not available for the NMAI case study.

4. Results

4.1 Reflected IR Imaging

The results of the reflected IR imaging of the three objects from the Freud Museum are illustrated with visible light images and reflected IR image details in figure 2. The IR images of the *Falcon-headed Figure* showed the contrast in reflection, transmission, and absorption between the brown-pigmented areas of the skin and clothing, which appeared lighter due to the transmission of IR radiation and the reflection from the gesso, and the lines, which appeared darker due to the higher IR absorption. Areas where IR radiation was absorbed appeared dark including linear designs and outlines of the face, eye, and details of the beak (fig. 2a); the outlines around the hip (fig. 2b); and the repetitive lines on the neck and chest (fig. 2c). The IR images of the *Human Headed Ba-Bird* showed the reflection, transmission, and absorption of the pigments used to decorate this object. The visibility of a crack on the proper left foot, an area of red pigment that is transparent with IR radiation, was increased in the IR image (fig. 2d). The contrast between the transparent green pigment on the head, wings, and base and the absorption of IR radiation revealed the fine details of cracks (fig. 2e, 2f). The IR imaging of the *Lekythos* showed the material used for past restoration as transparent and the underlying design absorbed the IR radiation (fig. 2g). The material used to depict the figures on the body of the vessel still absorbed IR radiation despite apparent fading or obstruction in the visible light image (fig. 2h). The smallest features estimated on the three objects were painted lines greater than 0.3 mm and cracks smaller than 0.1 mm (table 1). Feature measurements were estimated from still images calibrated using a measurement scale included in the image.

The results of the reflected IR imaging of the three NMAI objects are illustrated with visible light images and reflected IR image details in figure 3. The IR images of the *Inka Qero* showed the incised outlines of the figures and design elements with some of these fine lines extending into neighboring elements as seen in figure 3a (circles). The eye and hair, which are black in the visible light image, either disappeared in the IR image (the eye) or became a light grey (the hair) indicating little to no absorption of the IR radiation (fig. 3b arrow). An increased contrast of the fine lines that absorbed IR radiation enhanced the visibility of the craquelure (fig. 3b circle). The IR images of the *Inka Qero (Jaguar head)* showed the spots with missing materials as reflective and similar in tone to the brown pigment (fig. 3d circle). The enhanced contrast of the IR images emphasized cracks in the brown areas especially towards the rim of the vessel (fig. 3e), but fine cracks were not observed in the dark spots. The IR images indicated that two materials may have been used for some of the pelage-patterned spots. Parts of the spots became transparent, while a second material absorbed the IR radiation and remained dark (fig. 3f) resulting in an appearance of uneven application. The IR images of the *Vessel* showed an increase in the visibility of over painted fills and repairs on both the interior (fig. 3g) and the exterior (fig. 3h, 3i) of the object. The difference in reflection and absorption on the face of one of the figures suggested a different material was used for the repair (fig. 3i). The smallest features estimated on the three objects included incised lines 0.3-0.6 m, cracks about 0.1 mm, and design elements larger than 0.4 mm (table 1).

4.2 3D Imaging

The 3D imaging of the three objects from the Freud Museum resulted in textured photogrammetric models (fig. 4, left column) and non-textured white light scanned models (fig. 4, right column). The photogrammetry of the *Falcon-Headed Figure* produced a model with excess data under the arms (fig. 4a), a challenging area to document with both photogrammetry and white light scanning. The resulting white light scanned model had holes in the data for this area (fig. 4b). The photogrammetry of the *Human Headed Ba-Bird* produced a model with areas that resolved fine details of the coarse surface, while other details were blurred (fig. 4c). Areas of the model had uneven rough surfaces not representative of the object's actual surface especially between the legs and feet (fig. 4d). The white light scanned model appearing to have a smoother surface more accurately represents the object, including some pits and bumps (fig. 4e). However, this model had missing data, seen as holes, around the feet, legs, and base (fig. 4f). The photogrammetry of the *Lekythos* produced a model that resolved the surface geometry of a crack approximately 0.6 mm (fig. 4g) and additional crack details seen in figure 4h. The white light scanned data resulted in a model that resolved the same crack as figure 4g with increased clarity (fig. 4i), and a smooth surface appearing to be more truthful to the actual surface. However, this model also had missing data, seen as holes around the base (fig. 4j).

5. Analysis

5.1 Reflected IR Imaging of Three-Dimensional Cultural Heritage Objects

The imaging case studies at the Freud Museum and NMAI have provided examples of using reflected IR imaging for enhanced detail detection of three-dimensional cultural heritage objects. The IR images of the *Falcon-Headed Figure* and the *Lekythos* enhanced the visibility of design elements that had been obscured by reconstruction materials, fading, and wear. The IR images of the *Human Headed Ba-Bird* revealed cracks throughout the object (head, wings, and foot). The identification of these cracks can contribute to the understanding of the condition of the object.

The reflected IR images of the two NMAI qeros build on the long-term technical study (Kaplan et al. 2012; Newman, Kaplan, Derrick 2015) that provided information about the materials and manufacture. The lack of IR absorption of the hair and eye of the male figure on the *Inka Qero* suggested that the pigment is not carbon based as originally thought. The IR images of the *Inka Qero* showed the incised lines and inlaid resin proposed by Kaplan et al. (2012) as traditional qero manufacture techniques. In contrast to the craquelure pattern of the pigmented resin of the *Inka Qero*, the *Inka Qero (Jaguar head)* lacked craquelure in the pelage-patterned spots. The IR images of *Inka Qero (Jaguar head)* provided no evidence of incised lines, and the loss of material in the spots did not correspond to the craquelure and losses observed in the images of the *Inka Qero*. Comparison of the IR images for the two qeros suggests that the *Inka Qero (Jaguar head)* was not polychromed with the same methods and materials used for the *Inka Qero*; this is currently under investigation at NMAI.

The smallest features estimated from the reflected IR images included incised lines approximately 0.3-0.6 mm, cracks smaller than 0.1 mm, and design elements larger than 0.3 mm. While smaller details could be documented acquiring detail images with a standard camera or using microscopy, the presented results provide a general idea of some feature sizes that can be recorded when the entire object is in the field of view. Using a modified DSLR camera with the same resolution to the camera used for visible light documentation provided a high-resolution option for reflected IR imaging allowing for small features to be recorded.

5.2 Comparing Photogrammetry to White Light Scanning

In order to assess photogrammetry and white light scanning, evaluation parameters were selected based on a review of current publications in the field as discussed in section 1.3. These parameters include accuracy, shape discrepancies, and resolution. True values, or a "ground truth", were not available for the objects in the present study and, therefore, we were not able to evaluate accuracy of the models. Instead white light scanning results were used as the reference data for evaluating photogrammetry models, similar to the study by Koutsoudis, Vidmar, and Arnaoutoglou (2013) comparing photogrammetry models to laser scanning models.

Shape discrepancies between the photogrammetry models and the white light scanned data were visualized with deviation maps, false-color images indicating positive (yellow, orange, and red) and negative (turquoise and blue) shape differences (fig. 5). For example, the largest discrepancies in the *Falcon-Headed Figure* models were in the areas of the feet, beak, underarms, and hairline (fig. 5a). The feet and beak areas were slightly out of focus in many of the photogrammetry images, which could be improved by additional camera positions and increased depth of field. The areas under the arms and around the hairline were difficult to image as there was a loss of information from self-shadowing and the features presented fewer overlapping camera views. Similarly, the largest discrepancies in the *Human Headed Ba-Bird* models were in the areas between the legs and feet (fig. 5b). This area was not fully documented by white light scanning, and, therefore, the deviation maps show a difference between the photogrammetry and white light scanned model. In addition, the *Lekythos* model had discrepancies around its base and the crack details (fig. 5c) because the base and the depth of the cracks were not fully documented by white light scanning. The surface deviation map was green over most of the three objects indicating that the 3D models from photogrammetry and white light scanning are similar and a majority of the compared geometries are within ± 0.1 mm of each other.

Resolution (x, y) advertised by the manufacturer for the white light scanner was 0.1 mm for the 300 mm optics (Breuckmann SmartSCAN), which is not enough to resolve fine cracks that can be less than 0.02 mm (MacDonald 2010). Only the input images for the *Human Headed Ba-Bird* were in the suggested sampling resolution range (27-100 px/mm) to resolve the 0.02-0.075 mm features presented by MacDonald (2010). If most input images cannot resolve the features, then the resulting photogrammetry models will not resolve them either. The sampling resolution suggested by MacDonald (2010) may be more than what is needed, but the resolution needed is dependent on the object imaged and project objectives. The surface geometry of the photogrammetry models for this study were able to resolve cracks larger than 0.2 mm and incised lines averaging 1 mm, but not the finest crack details (< 0.1 mm). The photogrammetry texture was able to resolve some of the fine crack details and other features of interest including larger cracks, incised lines (> 0.2 mm), and painted design elements (> 0.4 mm). The features are presented as x, y measurements and the z dimensions and depth resolution are not addressed in this study.

6. Discussion

The reflected IR imaging of the six objects enhanced the visibility of design elements in the *Falcon-Headed Figure* and the *Lekythos*, revealed cracks in the *Human Headed Ba-*

Bird, and provided information about materials and manufacture for the *Inka Qero* and the *Inka Qero (Jaguar head).* The comparison of the resulting IR images for the two qeros suggested different materials and manufacture methods, which is continuing to be investigated. The reflected IR results from the documentation of these objects supports the use of the technique for three-dimensional objects to increase the visibility of obscured details, reveal surface features, and provide additional information about materials and manufacture.

Challenges for this study included presenting the results for visible light and reflected IR imaging, which required representing three-dimensional objects with 2D images. The IR image details of the objects are shown side-by-side in reference to visible light images. However, these are selected 2D views of the object, which do not fully represent the entire object. 3D imaging has potential to work beyond the limitations of 2D images in acquiring the full dimensionality of a three-dimensional object by recording the surface geometry and texture of an object. Integrating reflected IR with 3D imaging would allow the features recorded by reflected IR imaging to be more accurately mapped and provide insight about materials, manufacture, and condition. If reflected IR and 3D imaging can be integrated, the question then arises whether accessible 3D techniques can produce a model with sufficient resolution to document the details recorded with reflected IR imaging.

This research compared two 3D imaging techniques to discover whether there is a significant difference in the performance between these techniques and whether the techniques can resolve the features recorded in reflected IR imaging. Techniques like micro-CT scanning and 3D digital microscopy may provide high-resolution 3D geometric data at the micro scale. However, white light scanning was selected as a more expensive and specialized technique and photogrammetry as the less expensive technique using similar equipment to that of reflected IR imaging. The surface deviation maps comparing the models from white light scanning and photogrammetry show a close similarity mostly within ± 0.1 mm of each other.

The resulting models were not able to resolve some of the smallest features; however the resolution can be increased for both techniques. For white light scanning the resolution can be increased by reducing the field of view with the scanning optics. Several components can improve the resulting 3D data from photogrammetry. Reducing the working distance, changing the optics, and increasing the camera resolution can all increase the resulting resolution (Koutsoudis, Vidmar, and Arnaoutoglou 2013). Lighting is also very important; even, diffuse illumination and reducing the effect of shadows will improve the resulting data (Koutsoudis, Vidmar, and Arnaoutoglou 2013). Defining the documentation objectives and the finest features that need to be recorded can be used to estimate the best GSD for the project and to determine the distance needed between the object and camera or possibly the best lens or camera. For the current study the GSD was not calculated for each object instead a setup was used for a group of objects irrespective of the object and finest features. Additionally, calibrated scale bars can improve accurate measurement. Including coded targets in the imaging scene can improve accuracy (Sapirstein 2016). However, coded targets cannot be used in many applications for cultural heritage documentation if place directly on the object because the risk to the surface. An option could be to place coded targets around an object. Additionally, instead of coded targets, repeatability tests as discussed in Sapirstein (2016) and presented in Dellepiane et al. (2013) could be an option to better understand the accuracy and reliability of the resulting data as acquired in specific settings.

Researchers have presented photogrammetry as an accessible, portable, and flexible technique that can provide high-resolution results by a non-expert user for cultural heritage documentation (Abate et al. 2014; Nicolae et al. 2014). The camera equipment needed for SfM is not specialized and can be found in many conservation labs. The software can be freely available or purchased at a low cost and some options are user friendly, making the technique accessible for cultural heritage documentation. The equipment used for this study included a tripod and fit into an airplane carry-on size rolling case that can be transported easily illustrating the portability of the technique. The scalability of photogrammetry is also an advantage. It can document a range of materials and object sizes without additional equipment costs. Additionally, acquired images for photogrammetry can be reprocessed as the technology and algorithms continue to develop and improve. These are all advantages for photogrammetry that are considered when selecting the technique for cultural heritage documentation over other 3D imaging techniques.

SfM methods have been questioned by Remondino et al. (2012), Green, Bevan, and Shapland (2014), and Sapirstein (2016). Remondino et al. (2012, 42) stated that SfM 3D reconstructions should be used for visualization and not for photogrammetric or mapping purposes. Green, Bevan, and Shapland (2014, 181) concluded SfM is "a less accurate, but cheaper and higher resolution substitute" for some of the more expensive higher-end laser scanning techniques. SfM is widely used for cultural heritage documentation, but the question arises whether the method is providing reliable results that heritage professionals expect with a model that "looks good." Sapirstein (2016) reiterated Green, Bevan, and Shapland (2014) and the need to assess the accuracy of photogrammetry reconstructions if used for measurements. Some of the photogrammetry reconstructions presented in the current study were compared to white light scanned data providing a relative idea about the reliability of the resulting geometry. However, the white light scanned data does not provide a ground truth and many 3D imaging campaigns will not and cannot include two techniques to document each object and assess the accuracy of the photogrammetric reconstructions.

There is still a need for established best practices for documentation of three-dimensional cultural heritage objects and assessing the accuracy of the resulting 3D models. While 3D imaging techniques can be accessible to the non-expert user, especially SfM, specialist knowledge and the experienced user can improve the accuracy and reliability of the resulting data. If a 3D model is to be used for measurements and more than visualization, it is important to have an understanding of the accuracy and reliability of the technique and resulting data. Having a model that "looks good" does not mean that it can be used for metric applications. Hess (2015) notes that 3D data of museum and archaeological objects can be highly inconsistent including variation in geometric accuracy, resolution, and color (31) and that skills of the operator can impact the 3D imaging results (182). Working towards best practices, Andrews, Bedford, and Bryan (2015) provide metric survey specifications for mostly monuments and built heritage, and Hess (2015) presents the creation of a prototype portable 3D test standard specifically for heritage applications that will allow comparison of geometry, color, and spatial resolutions among 3D imaging systems. As 3D imaging continues to be widely used, an awareness is needed that interrogates the intended use of the 3D models and whether the technique and resulting data can support that use.

7. Conclusions

Reflected IR imaging allows the enhanced detection of details, which is known from its established uses as an investigation tool in conservation for two-dimensional and three-dimensional objects. The resulting documentation of the objects from the Freud Museum and NMAI support the utility of reflected IR imaging of three-dimensional objects for enhanced detection of details: increasing visibility of obscured details, revealing surface features that indicate the condition, and providing information about materials and manufacture.

The resulting 2D IR images do not fully represent the three-dimensional object. The integration of reflected IR and 3D imaging could provide an effective way to visualize and map the resulting IR imagery and to increase accuracy of the spatial location of the details. The present study assessed white light scanning and photogrammetry to investigate whether an accessible 3D imaging technique could resolve similar detail to reflected IR imaging. The key conclusion of the comparison is that the resulting models are similar and neither was able to resolve some of the smallest features recorded by reflected IR imaging. However, the resolution for both techniques can be increased. Defining the objectives of imaging to plan the setup and acquisition ensure that the appropriate resolution is used to document the objects.

The advantages of cost, portability, flexibility, and accessibility of photogrammetry present a promising option for the integration of IR and 3D. Given the examples of reflected IR imaging for enhanced detection of details and photogrammetry or white light scanning to resolve fine details, the integration of reflected IR and 3D imaging could provide a multi-layered view and an enhanced understanding of an object.

Acknowledgments

This research is part of an MRes and PhD in Heritage Science at University College London and University of Brighton through the Science and Engineering Arts Heritage and Archaeology (SEAHA) an EPSRC funded Centre for Doctoral Training. Project partners included the

Smithsonian’s Museum Conservation Institute, the Freud Museum, and Analytik Ltd. Project advisors included Matija Strlic, Roger Evans, Robert Koestler, Ian Laidlaw, and Karina Rodriguez-Echavarria. The author would like to thank the Freud Museum staff especially Daniel Bento, Bryony Davies, Carol Seigel, and Francisco da Silva. The Cultural Information Research Group (CIRG) at the University of Brighton provided access and use of the Breuckmann 3D scanner, and Dean Few provided technical training and support. The imaging and research at NMAI would not have been possible without the wonderful help and support of Emily Kaplan and Caitlin Mahony. The author would like to thank the staff at MCI especially for the advice and support of Paula DePriest. None of this would have been possible without the inspiring work, passion, and example of Melvin J. Wachowiak (1958-2014).

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Sources of Materials

Canon 5D Mark II, Lowel ViP Pro-Light
B&H Photo Video
420 9th Ave.
New York, NY, 10001, USA
866-254-1492
http://www.bhphotovideo.com

UV + IR + Visible Camera Modification
MaxMax
220 Broad St.
Carlstadt, NJ, 07072, USA
201-882-0344
http://maxmax.com

Coastal Optics UV-Vis-IR 60 mm APO Macro lens
Jenoptik Optical Systems
16490 Innovation Drive
Jupiter, Florida, 33478, USA
561-881-7400
http://www.jenoptik-inc.com

Agisoft Photoscan
Agisoft LLC
11 Degtyarniy per.,
St. Petersburg, Russia, 191144
+7(812) 621-33-41
http://www.agisoft.com/

Breuckmann SmartSCAN, Breuckmann turntable, OptoCAT 2014 software
Breuckmann GmbH
Torenstraße 14, 88709
Meersburg, Germany
http://aicon3d.com/

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computational imaging techniques to aid in the research and conservation of Smithsonian collections.

Table 1. Resolution and resulting details

	Resolution of still images (px/ mm)	Smallest features (mm):
Falcon-Headed Figure	20	Painted lines > 0.9
Human Headed Ba-Bird	28	Painted lines > 0.3; Cracks < 0.1
Lekythos	20	Painted lines > 0.5; Cracks < 0.3
Inka Qero	19	Incised lines 0.2; Cracks < 0.1; Design elements > 0.4
Inka Qero (Jaguar)	13	Cracks > 0.2; Design elements > 1
Vessel	24	Incised lines 0.4-1; Cracks > 0.1

Figure 1. Six objects used as case studies: Freud Museum (top row) and NMAI (bottom row) case studies: (a) *Falcon-Headed Figure*, 27 x 6 cm (LDFRD 3124); (b) *Human Headed Ba-Bird*, 14 x 6 x 12 cm (LDFRD 3286); (c) *Lekythos*, 23 x 9 cm (LDFRD 3702); (d) *Colonial Inka Qero*, 18 x 14 cm (NMAI 16/3605); (e) *Colonial Inka Qero (Jaguar head)*, 23 x 15 cm (NMAI 10/5860); and (f) *Vessel*, 13 x 13 cm (NMAI 23/9575)

Figure 2. Visible light images and reflected IR details of the Freud Museum objects: ***Falcon-Headed Figure*** (a) IR detail of lines around the face, eyes, and beak; (b) IR detail of lines depicting clothing around the hip (arrow); and (c) IR detail of the repetitive lines on the neck and chest (arrows). ***Human Headed Ba-Bird***: (d) IR detail of a crack across the proper left foot of object (ellipse); (e) IR detail of the cracks in the head of the figure (circle); and (f) IR detail of the cracks in the proper left wing (arrows). ***Lekythos****:* (g) IR detail of the design with IR radiation penetrating repair

materials (circle) and (h) IR detail of a figure on the body of the vessel absorbing IR radiation.

Figure 3. Visible light images and reflected IR details of the NMAI objects: ***Inka Qero***: (a) IR detail of the incised lines (circles); (b) IR detail of the hair of the male figure (arrow) and the craquelure pattern of the pigmented resin (circle); and (c) IR detail of the craquelure and loss of inlaid material (arrow). ***Inka Qero (Jaguar head)***: (d) IR detail of pelage-patterned spots with area of missing material (circle) and the fine crack (arrow); (e) IR detail of the craquelure at the rim of the object (arrow); and (f) IR detail of the uneven dark spots. ***Vessel***: (g) IR detail of material that absorbed IR significantly more than surrounding material; (h) IR detail of past repairs and fills (arrows); and (i) IR detail of overpainted crack and different material used for face of figure (arrows).

Figure 4. Textured view of photogrammetry models (left column) and white light scanned models (right column) of Freud Museum objects: ***Falcon-Headed Figure*** (a) solid view detail of excess data under the arm of the figure (circles) and (b) detail view of missing data under the arm of the figure (arrow). ***Human Headed Ba-Bird*** (c) Textured view of varying resolution of facial details (eye is blurred and cheek resolved sand-like detail); (d) Solid view of photogrammetry model and the uneven, rough surface between legs and feet; (e) Detail of pits and bumps on the face and a smooth surface roughness; and (f) Detail view of areas of missing data. ***Lekythos***: (g) Solid view resolving detail of crack; (h) Wireframe view of missing piece and cracks; (i) Detail view of same crack as figure 4g; and (j) Detail view of base with areas of missing data**.**

Fig. 5. Deviation maps illustrating the shape difference, or surface deviation, of the photogrammetric models compared to the white light scanned models. The deviation maps were created using GOM Inspect software: (a) *Falcon-Headed Figure*; (b) *Human Headed Ba-Bird*; and (c) *Lekythos.*

To the Senior Editor and Associate Editor,

Thank you so much for accepting the paper. I have made the changes that you and the reviewers have included. I have not provided responses as I agree with the suggestions and have made the changes accordingly. This document includes the reviewers' comments followed by the changes made.

Thank you,
Keats

List of Changes

I have updated the text to include the sections and subsections (ie 2., 2.1, etc) as requested. Additionally the Acknowledgments now follow the Conclusions section and the Author Bio follows the Sources of Materials. The final component of the text in the Word document is the table and the figure captions.

Reviewer #2: It is generally clearly written. The author should review a sentence on page 13: "Linear designs and outlines of the face, eye, and details of the beak", as it does not appear to be a full sentence.
I have rearranged this sentence so that it does not appear to be incomplete. The sentence now reads:

> Areas where IR radiation was absorbed appeared dark including linear designs and outlines of the face, eye, and details of the beak (fig. 2a); the outlines around the hip (fig. 2b); and the repetitive lines on the neck and chest (fig. 2c).

Reviewer #2: The image captured with reflected IR technique is not a simple reflection and absorption of IR radiation. The "grey scale" seen in a reflected IR image is the result of materials' transparency, reflectivity, and absorbency to IR. If a section recorded white, it could mean two things: the materials are highly reflective to IR or the top materials are transparent to IR and the under layer is highly reflective. In the case of the first object, Falcon-headed figure, the brown-pigmented areas of the skin and clothing appear to be transparent to IR, instead of highly reflective as explained by the author. The "white" should be from the gesso which is highly reflective to IR. The author should make adjustments to any section that uses reflective to define a white IR result.

Check the areas:
1. Page 13, "brown-pigments…due to higher IR reflection" (should be transparency)
This sentence has been updated to read:

> The IR images of the *Falcon-headed Figure* showed the contrast in reflection, transmission, and absorption between the brown-pigmented areas of the skin and clothing, which appeared lighter due to the transmission of IR radiation and the reflection from the gesso, and the lines, which appeared darker due to the higher IR absorption.

2. Page 13, "The visibility of a crack….an area of IR-reflective red pigment" (should be transparent)
This sentence has been updated to read:

> The IR images of the *Human Headed Ba-Bird* showed the reflection, transmission, and absorption of the pigments used to decorate this object. The visibility of a crack on the

proper left foot, an area of red pigment that is transparent with IR radiation, was increased in the IR image (fig. 2d).

3. Page 14, "The reflectance of the IR radiation by the red and brown-pigmented resins…. " The contrast is due to highly reflective ground and the absorbing fine lines. The transparency of the pigmented resins allows the IR to reflect back from the ground.

This sentence has been updated to read:

> An increased contrast of the fine lines that absorbed IR radiation enhanced the visibility of the craquelure (fig. 3b circle).

4. Page 14, "The difference in reflection and absorption on the face of one of the figures…" This is correct. There is no top coat and the greyness is the direct result of the reflectivity of the materials there.

The author cannot locate Figure 2i. I think Figure 2h in the paper is supposed to be Figure 2g, and Figure 2i is supposed to be 2h.

The figure references on page 13 have been updated to (fig. 2g) and (fig. 2h) instead of (fig. 2h) and (fig. 2i).

The difference between PECA 906 and 87C is more than just "maximize the transparency" and "general use". They are two different types of filters. The good old standard in filtration for IR photography is a set of Kodak Wratten filters (longpass filters on gelatin substrate) from 88A, 87, 87C, 87B, to 87A with different cut off wavelengths. They are in square format, and usually require a filter holder to fit onto the lens (loosely). PECA company produces different IR filters on glass base as screw in filters for ease of use. The set of PECA longpass filters are manufactured to match Kodak Wratten filters. In the case here, PECA 906 is "equivalent" to 87A. So it is correct that PECA 906 will cut off more IR than 87C, but it is not a fair comparison. It should explain that PECA 906 is chosen because it is equivalent to 87A, a filter that has the capacity to cut off most shorter wavelength IR. As materials become more transparent to longer wavelengths, it is reasonable to use 87A (or PECA 906) to block shorter Near IR wavelengths.

The caveat for using 87A or PECA 906 is its long exposure due to the very low sensitivity of the CMOS sensor after 950nm. The images tend to have more noise

My suggestion is to delete "as opposed to a Kodak Wratten 87C that may be for more general use."

The part of the sentence that reads "as opposed to a Kodak Wratten 87C that may be for more general use" has been deleted as suggested. The updated sentence reads as follows:

> The Peca 906 longpass filter, comparable to the Kodak Wratten 87A filter, was selected as it cuts off shorter IR wavelengths and could maximize the transparency of some materials.

Regarding the coded target. The author wrote, "coded target cannot be used in many applications for cultural heritage documentation because of the risk to the surface of the object" (page 20)" if applied directly to the object. However, it should be an option to place the coded targets along with the object, not on the object.

These sentences have been updated to read:

> However, coded targets cannot be used in many applications for cultural heritage documentation if place directly on the object because the risk to the surface. An option

> could be to place coded targets around an object. Additionally, instead of coded targets, repeatability tests as discussed in Sapirstein (2016) and presented in Dellepiane et al. (2013) could be an option to better understand the accuracy and reliability of the resulting data as acquired in specific settings.

Additional changes:

p1 Abstract:
Initially the sentence read "The study asses the two 3D imaging…"
The sentence now reads:

> The study assesses the two 3D imaging techniques, one more expensive and the other more accessible, to discover whether there is a significant difference in performance for the purpose of resolving the details recorded by reflected IR imaging.

p4
"Falco (2009) included a single example, a set of Japanese armor, where the technique was used for material identification."
The sentence initially included "identification" as seen above, but now includes "differentiation".

p18
"This research compared two ~~such accessible~~ 3D imaging techniques to discover whether there is a significant difference in the performance between these techniques and whether the techniques can resolve the features recorded in reflected IR imaging."
"such accessible" was deleted from the above sentence.