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Imaging Techniques in Conservation

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This paper explores the potential uses of new imaging techniques within conservation and their potential implications for object preservation and accessibility. Study of such implications is crucial because employment of these imaging techniques is increasingly common and becoming irreplaceable. For example, polynomial texture mapping (PTM) has revealed previously undetectable surface features; this makes it necessary to continue to use the technique to monitor object condition. 3D laser scanning and certain applications of CT scanning are also examined.

The findings indicate that the techniques present some advantages over standard digital photography. The 3D models produced by laser and CT scanning, and the high-resolution texture maps created with PTM enable changes in surface features to be tracked and recorded.

PTM is found to be particularly useful and affordable. A more established role within conservation, especially for condition assessments, would be worthwhile. Use of the imaging techniques to create digital and physical models for exhibitions can also be advantageous. However, such models must be used to enhance understanding of original objects, not to reduce accessibility to them.

Introduction

A range of sophisticated imaging techniques has been developed in recent years. These are being exploited in increasingly imaginative ways across the cultural heritage sphere. This paper examines their use and potential use within conservation, covering three important techniques: 3D laser scanning, polynomial texture mapping (PTM), and innovative applications of CT scanning.

3D Laser Scanning

3D laser scanning creates 3D images from 'point clouds' mapping objects. The laser beam is reflected by the object and recorded by a sensor producing data points that construct an object map. In colour laser scanning the red(R), green(G), and blue(B) wavelengths are measured to give an RGB value as well as an XYZ coordinate (Hess and Robson 2010: 289).

There are two main types of laser scanning: time-of-flight and triangulation. Triangulation is used for smaller objects. It can be used to calculate XYZ coordinates for the point cloud because there is a fixed, known distance between the laser source and sensor (Bryan 2006: 164). Triangulation has good accuracy (typically 50μm) but a relatively restricted operating range (c.0.1m–1m). The operating range can be extended to approximately 25m using a mirror or prism-based system to scan the object rather than an arm-mounted scanner or rotation stage. However, deterioration of accuracy is generated at this higher range (Jones 2007: 7–8). The fixed distance required between laser source and sensor also restricts the size of objects that can be scanned (Bryan 2006: 165).

Time-of-flight scanning, also known as LiDAR (Light Direction and Ranging), sends a laser pulse towards the object and generates the point cloud by calculating the length of time the laser takes to be reflected back to the scanner (Bryan 2006: 165–6). This is not restricted by the need for a fixed distance between laser source and sensor. Therefore, time-of-flight scanners are more portable and capable of greater object-to-sensor range (c.2m–100m) enabling imaging of larger objects and sites (Jones 2007: 7). Time-of-flight scanning can also be performed day or night, whereas triangulation can be disrupted by bright sunlight (Bryan 2006: 165–6). However, time-of-flight scanning is less accurate (c.3–6mm) than triangulation (Jones 2007: 7). Therefore, for most museum objects triangulation-based scanning is more appropriate.

CT Scanning

CT scanning (X-ray computed tomography) produces 3D images that can display both the interior structure of objects and their surfaces. A series of virtual 2D cross-sections is taken by rotating the X-ray source and detector around the object. These depict radio-density, the principle that materials block or transmit X-rays to different extents. The closer a pixel is to white, the more radio-dense the material it represents. These 2D images are combined to form a black and white 3D image (Warren 2009). The process is automated, producing high-resolution images (c.50μm) and is not affected by lighting conditions (Velios *et al.* 2003). Advances in micro-CT scanning mean that high resolution (3–5μm) rendering of very small objects is now also possible, as demonstrated by the Natural History Museum, London (Nikon Metrology 2009; Natural History Museum Website 2012).

PTM (Polynomial Texture Mapping)

PTM was created in 2000 by Tom Malzbender at Hewlett Packard (HP) Labs (Malzbender *et al.* 2001). It is a reflectance transformation imaging (RTI) technique used to create texture maps of objects. These are composed from multiple digi-

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Fig. 1: Portus brick stamp. Range of images enabled by PTM. Clockwise from top left: flat light, specular enhancement, diffuse gain, surface normals, and four images with different directional raking lights. (Earl *et al.* 2010: 2046. Figure 9).

tal images, with different illumination directions (**figure 1**). Different types of RTI store surface reflection information per pixel in different ways. PTM is the most common type of RTI used within cultural heritage (Happa *et al.* 2009).

Each pixel in the PTM stores both colour information and 'normal' values. Normals are vectors perpendicular to the object surface. They represent surface shape and enable calculation of light reflection, allowing the object image to be artificially relit from different directions to reveal surface texture. Therefore, PTMs are interactive 2D images that appear 3D.

To create a PTM, illumination direction must be either known in the source images or determinable from them. For the former, lights are mounted using a mechanical rig, arc or dome and the known positions of the lights are programmed into the PTM software (**figure 2**; Mudge *et al.* 2006: 3). In the latter, a moveable light can be employed if a specular black or red sphere is positioned with the object in the camera frame. This is called 'highlight PTM'. A highlight is created on the sphere and the software can determine the light position from the location of this highlight (Mudge *et al.* 2006: 4–5). This technique can also be performed under microscope using ball bearings as specular balls (Earl *et al.* 2011: 150).

Once created, the light qualities applied to the PTM can be altered using diffuse gain and specular enhancement to enable better analysis of surface features. Specular enhancement produces an artificially shiny appearance and diffuse gain gives a matte appearance providing increased tonal contrast (Earl *et al.* 2010: 2042). Specular enhancement also enables complete surface information to be gathered where data loss would normally be incurred by specular reflection, provided that a sufficient number of source images are taken for all surface normals to be calculated (**figure 3**; Mudge *et al.* 2005: 7).

The analytical capabilities of these technologies combined with their non-contact nature mean that they are potentially very useful for investigating objects. The detailed images produced can be beneficial from a functional conservation perspective to monitor and record condition and can be used within exhibitions and online to enhance object exploration and reach a broader audience. This suggests that wider introduction of the techniques would be beneficial for conservation and display.

There is little doubt that such techniques are currently being applied creatively and advantageously. However, there is also little uniformity in these applications. Various groups and institutions working within cultural heritage are now using them for a range of different functions. As they start to become irreplaceable tools for discovery and documentation, it is appropriate that certain questions are asked to ensure widespread understanding of the ways that they can, and are, being used.

Conservators need to address the appropriateness of the current role of such techniques within conservation and if it should be expanded. This requires examination of their capabilities and suitability for practical conservation work and documentation, as well as their effects on object preservation and accessibility. This paper presents a starting-point for this objective and attempts to answer the following questions:

- How are these imaging technologies currently employed for cultural heritage applications?
- What are the advantages, disadvantages and risks of the technologies?
- What are the implications of these technologies for preservation of and accessibility to objects?

The main aim of the paper is to examine how the process of imaging can affect objects and how useful the images produced might be for aiding object conservation. The

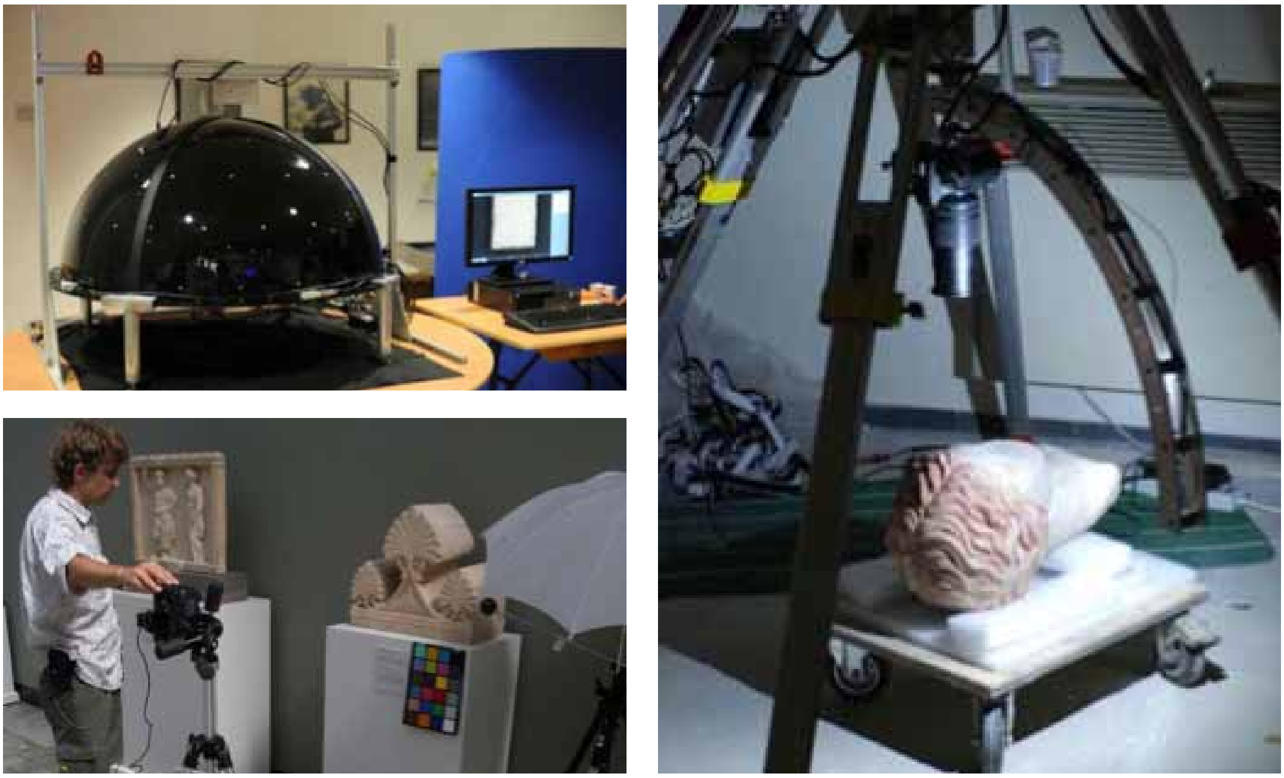

Fig. 2: Clockwise from left: PTM dome; rig; highlight capture. (Earl *et al.* 2011: 148, 150. Figures 2, 1 and 6).

Fig. 3: Unrolled lead amulet with Mandaic inscription (c. 5th century AD, Iraq). © Ashmolean Museum AN1931.474. (Above) Ordinary digital image: some of inscription obscured by corrosion. (Below) PTM under specular enhancement: inscription clearer and other surface details more apparent. (Piquette *et al.* 2011. Figure 4).

Fig. 4: PTM of Herculaneum Amazon statue lit from various directions. Diffuse gain and specular enhancement can also be adjusted. Screenshots captured from the interactive PTM presented at Southampton University Website, Archaeology Computing Research Group.

conclusions draw upon ideas discussed with respect to the advantages and disadvantages of the techniques, and implications of their use, to establish how they can be most appropriately used within conservation and whether use should be expanded.

Current Use of Imaging Technologies within Cultural Heritage

Use of these technologies has become increasingly widespread but they are not yet part of standard conservation procedures. However, various experimental projects have produced promising results for conservation.

PTM

The RTISAD Project (Reflectance Transformation Imaging System for Ancient Documentary Artefacts) at the Universities of Oxford and Southampton is the most significant initiative in the UK investigating PTM.

Pilot RTISAD programmes have successfully imaged inscribed documents, including cuneiform tablets, to enable reading of inscriptions not visible under normal conditions. Other archaeological objects including a Herculaneum Amazon statue and a ceramic roundel from Greece have also been imaged to test the usefulness of PTM for documenting surface condition of artefacts (**figures 4 and 5**). The latter involved PTM conducted under microscope and enabled examination of salt efflorescence and deposition, craquelure, and flaking and loss of pigment (Earl *et al.* 2009: 25; Earl *et al.* 2011: 149–150).

At the Fitzwilliam Museum, the RTISAD project has helped to produce PTMs of Islamic medieval lustre and *Mina'i* ware (Fitzwilliam Museum 2012). The aim was to allow visitors to fully appreciate the aesthetic qualities of these glossy objects, which is not possible in static displays behind glass. However, the PTMs also revealed cracking and pitting under specular enhancement that was not clear to the naked eye (Bridgman and Earl 2012).

PTM was similarly investigated by the National Gallery and Tate to assess its usefulness for imaging the surface of paintings to determine if it could present a viable alternative to the established method of raking light photography (Saunders *et al.* 2006). This concluded that it is an effective tool for documenting changes in condition and could be used to assess paintings during structural treatment and before and after loan (Padfield and Saunders 2005). PTMs were found to be more easily repeatable than raking light photographs, which rely heavily on the angle

Fig. 5: Microscopic PTM of ceramic roundel from Derveni, Tomb A, Greece. Area captured is 0.3mm across (Earl *et al.* 2011: 150. Figure 7).

and illumination direction selected and are difficult to recreate precisely in order to compare subsequent sets of images effectively. PTM provides an accurate representation of the entire texture of the painting, irrespective of the lighting positions employed to create it. Application of diffuse gain and specular enhancement also enabled surface features to be accentuated to a greater degree than possible with raking light photography.

3D Laser Scanning

The 3D Encounters Project at the Petrie Museum of Egyptian Archaeology (with Arius3D) aims to use 3D laser scanning to create a high quality 3D image library of artefacts and enable digital travelling exhibitions of fragile Egyptian artefacts (**figure 6**; 3D Encounters 2012). English Heritage has investigated the use of 3D laser scanning for a wide range of applications to gain archaeological and condition data (Jones 2007). The Liverpool Conservation Centre has also produced 3D laser scans on commission, including portable object and *in situ* scans of archaeological sites (Liverpool Conservation Centre Website 2012).

CT Scanning

High-resolution CT scanning has been employed by the EDUCE (Enhanced Digital Unwrapping for Conservation and Exploration) Project at the University of Kentucky. Papyrus scrolls are imaged in slices to distinguish between pigment and substrate layers and create a geometric model of the scroll and its surface texture, which can be virtually unwrapped and digitally flattened. Experiments have shown the general principles of this technique to be sound (Seales 2005).

A Deutsche Forschungsgemeinschaft (DFG) funded study has investigated CT scanning of objects contained within soil blocks lifted from the early medieval cemetery of Lauchheim in Baden-Württemberg (Stelzner *et al.* 2010). Unlike ordinary 2D radiography, which can provide some useful information primarily regarding metal artefacts, CT

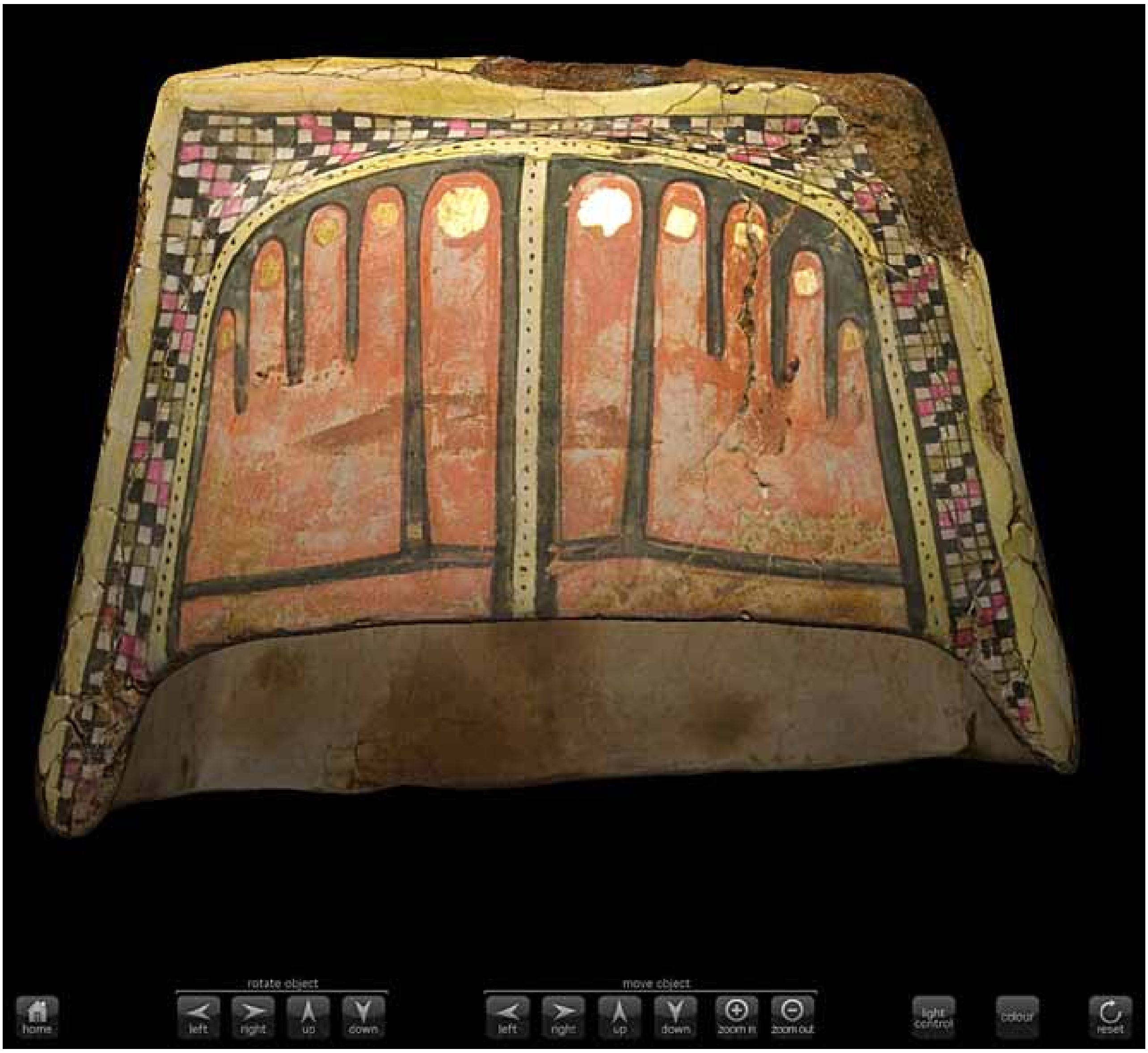

Fig. 6: Foot cover UC45893 © The Petrie Museum of Egyptian Archaeology, University College London. One of the digital images created by 3D laser scanning.

Fig. 7: Epoxy resin 3D model of shrew skull (enlarged) with visible contour lines. Image taken by the author. © The Natural History Museum, London

scanning has successfully been used to image objects also made from organics, ceramics and glass, and to determine their stratigraphical positioning. This enables quicker, more targeted excavation.

CT scanning has also been used by the Natural History Museum (London) to create images of natural history specimens and produce physical models with 3D printing to establish if this could be used to replace the traditional invasive method of moulding and casting. Synthetic models can be made using 3D printing through nylon laser sintering or building up resins (**figure 7**). Metal replicas can also be made by casting them from synthetic moulds made by 3D printing; stone replicas can be made by inputting 3D imaging data into automated appliances such as CNC machines (Jones 2007: 25). However, findings showed that casting currently still produces more accurate models. CT scanning produces accurate data but current 3D printing techniques incur loss of surface detail and those constructed from resins often display visible contour lines.

With the exception of the EDUCE and DFG projects, all of these cases are UK-based. They provide a good reflection of current uses of new imaging technologies within the UK. It is clear that application of these technologies within cultural heritage, and particularly within conservation, is mainly experimental or conducted on a case-by-case basis. Typically, the main focus of these applications has not been on conservation but on enabling better access to object details either for scholars or the general public. Nevertheless, many of the projects, particularly those relating to PTM, have demonstrated that use of these techniques within conservation can present considerable advantages. In spite of this there has been no widespread adoption of PTM across institutions in the UK.

In the US there has been better uptake of PTM. This is primarily because of the California-based group, CHI (Cultural Heritage Imaging), which has been pivotal to the development and dissemination of PTM across the US. They have published papers documenting the progress and outcomes of their own research into the technology, and held PTM training events for conservators and other interested parties at a range of institutions across the US. PTM is now regularly used for condition assessments by the conservation departments in many of these institutions (M. Mudge *pers. comm.* 2011). As the RTISAD project continues its work in the UK, it is likely that understanding of PTM and the advantages it can offer will also become more widely recognized in this country.

CT scanning suffers from a similar lack of recognition; its more 'traditional' uses, such as imaging Egyptian mummies are well known, but most other potential applications are not. Uses of laser scanning are better recognized and more commonly employed for creating digital models for display and documentation. Its application for reconstruction of fragmentary objects has also been investigated in the US (Velios *et al.* 2003: 88; Brown *et al.* 2008). However, it is not routinely used to its full potential.

Risk Assessment

Any new technique requires risk assessment. For new imaging techniques to be introduced, the benefits should outweigh potential risks. The main risks posed by these techniques are from electromagnetic radiation (e.g. light) and object handling.

The risk presented by light is similar in both PTM and standard digital photography. The threat is somewhat increased in PTM because a whole series of digital photographs is taken. The risk assessment conducted by project conservator Flavio Marzo for the Greek MSS Digitisation Project at the British Library found that the camera flash constitutes a negligible risk for most materials (Marzo 2009). However, the more intense light produced by 3D laser scanners may represent a greater threat and an appropriate strength of laser must be selected (Jones 2007: 10–11).

CT scanning involves X-rays, a higher energy and potentially more damaging form of electromagnetic radiation. Risk caused by light should be assessed for every object to be imaged. For example, a dose (illumination x time) calculation can be made and compared with 'safe' doses for the material(s) involved (Ashley-Smith 1999). Illumination by any intense electromagnetic radiation (including visible and UV light, and X-rays) can incur oxidation damage, especially in organic materials. Safe X-ray levels for CT scanning may be calculated by finding the mass absorption coefficient (extent to which X-rays are absorbed) of the material and its thickness to determine how much energy is absorbed; this can be compared with human dose limits to estimate risk of damage. However, since damage is cumulative and the techniques capture data very quickly, it is unlikely that light would pose a significant risk for any but the most sensitive materials (Mantler and Schreiner 2000: 7).

For most objects, handling remains the biggest threat. Everyone involved with imaging projects must have training in object handling. Although the techniques are non-contact, the objects may need to be moved to the imaging equipment and repositioned during image capture. Each stage of the imaging process must be planned ahead, including how and where objects need to be transported and if the object requires specialized support. Where possible, delicate objects should be imaged whilst held within their original mounts. For single-view PTMs, this should not be a problem. For 3D laser scanning, it may be necessary to use several different mounts to support the object whilst it is imaged from different angles; use of equipment such as a gantry is recommended so that the scanning equipment moves around the object instead. Environmental risks must also be recognized. If an object is housed in a closely climate-controlled environment, the effects on the object from disruption to its environment must be evaluated.

Once the whole process has been planned, a general risk assessment should be conducted, assessing each stage of the plan, potential hazards and how they may be dealt with. Adjustment to the plan may be necessary, depending on the results of the risk assessment. This will also contribute towards creating a standard protocol for the procedure, which should detail pre- and post- imaging condition assessment procedures, how and where imaging will take place, and specifications of the equipment used.

In addition to risks posed during the imaging process, there is the possibility that greater use of digital and physical models in exhibitions will cause objects to spend more time in storage. Effects on preservation caused by extended periods in storage can be positive or negative depending on the appropriateness of the storage conditions. However, unduly extended stays in storage should be discouraged for reasons of accessibility.

The main advantage common to all three techniques is the fact that they are non-contact technologies. The potential to reveal detailed information about objects

Advantages and Disadvantages – Comparative analysis of CT scanning, 3D laser scanning and PTM

	Non-contact	Colour	Resolution	Cost	Geometric data
3D LASER SCANNING	✓	✓	Good (c.50μm)	High About £3000+	✓
CT SCANNING	✓	×	Very good (c.50μm/3–5μm for micro-CT scanning)	Very high About £200,000+	✓
PTM	✓	✓	Very good c.2–8μm (equivalent to that of digital photography)	Low-medium $350 for a starter kit from CHI (CHI Website 2012)	Can be produced in conjunction with structured light scanning; however, this is complicated (Mudge *et al.* 2005: 9)

Other advantages	Other disadvantages
3D LASER SCANNING	
· Can scan both small objects and very large buildings and sites.	· Training is necessary, particularly because of the potential dangers associated with lasers (Jones 2007: 11). · Image resolution and accuracy of geometric data decreases with equipment used for larger objects and sites (Jones 2007: 7). · Data post-processing is complex, requiring considerable training. However, improved software is reducing this issue (Karsten and Earl 2010: 19). · Inappropriate for imaging black and/or highly specular materials e.g. polished marble or gilded surfaces (Jones 2007: 7; Bryan 2007: 18), or fluffy materials (fur/feathers) (Cignoni and Scopigno 2008).
CT SCANNING	
· Enables investigation of internal structure of objects.	· Objects must fit into scanning tunnel.
PTM	
· Can be used under microscope to reveal very small surface features. · Can be used to image specular objects (e.g. Bridgman and Earl 2012). · Free software is available for creating PTMs (from HP and CHI) (HP Website 2012; CHI Website 2012). · Although 3D geometric data is difficult to produce, the surface normals can be used for haptic virtual models (Bridgman and Earl 2012).	· Processing images to make PTMs is fairly complicated and some training may be required. Improved software is reducing this issue. · Provides only one fixed view of an object. However, multi-view PTM (POM (PTM Object Movie)) has been achieved (Mudge *et al.* 2006).

without touching them is clearly advantageous to conservation. The geometric data produced by both CT scanning and 3D laser scanning is useful for production of 3D models and reconstruction of fragmentary artefacts. For example, the Princeton Graphics Group has used 3D laser scanning to reassemble fragmentary wall paintings (Brown *et al.* 2008: 7; Toler-Franklin *et al.* 2010; Funkhouser *et al.* 2011). Precisely fitting object mounts may also be created from this data.

Accurate geometric data also means that scans taken over a period of time can be mapped onto each other to quantify material loss, damages or changes caused by factors such as handling, weathering and interventive conservation work. Furthermore, the geometric model can be employed to determine surface exposure to contaminants such as dust, which can vary across an object depending on factors such as curvature. Results can help to develop appropriate cleaning procedures (as for the statue of David by 3D laser scanning (Scopigno and Cignoni 2004)).

Although both CT scanning and 3D laser scanning offer these facilities, 3D laser scanning presents several advantages: it is less expensive, can produce colour images and scan large objects (such as David) in situ. CT scanning can be more appropriate for producing data for fitting mounts to very fragile objects. Such objects may be difficult to move around to image from all angles using a laser scanner; however, the penetrative capabilities of CT scanning mean that it can 'see' through the object without having to move it physically. CT scanning is also of particular use for objects with potentially interesting concealed internal parts. However, because of the very high costs involved, it is likely that 3D laser scanning will be preferred to CT scanning unless an institution already has easy access to a CT scanner. Certain institutions (e.g. the Natural History Museum, London) may establish themselves as centres for expertise in CT scanning and other museums may send artefacts to these institutions for work on commission.

Colour can be digitally removed from images produced from 3D laser scanning if useful for concentrating on surface texture (**figure 8**). Directional light (e.g. raking light) can also be applied to highlight surface details even more effectively (**figure 9**; Jones 2007: 14; Blais *et al.* 2007: 5).

Whilst 3D laser scanning can produce accurate geometric data and is sufficient for quantifying material loss, the resolution provided is not typically as good as that from ordinary digital photography, as used to construct PTMs. The superior resolution afforded by PTM combined with the ability to interactively adjust the images using diffuse gain and specular enhancement, and by changing the light direction means that PTM can be more suitable for documenting fine surface detail than laser scanning.

Such features provide PTM with a number of advantages over standard digital photography, particularly for imaging objects with relief. For a digital photograph to represent all features of an object, there should be good tonal contrast. However, because different features may become visible only when lit from particular angles, it is difficult to achieve sufficient tonal contrast to highlight certain features without obscuring others. PTMs can be analysed to determine the best lighting direction to highlight all features, together with applying specu-

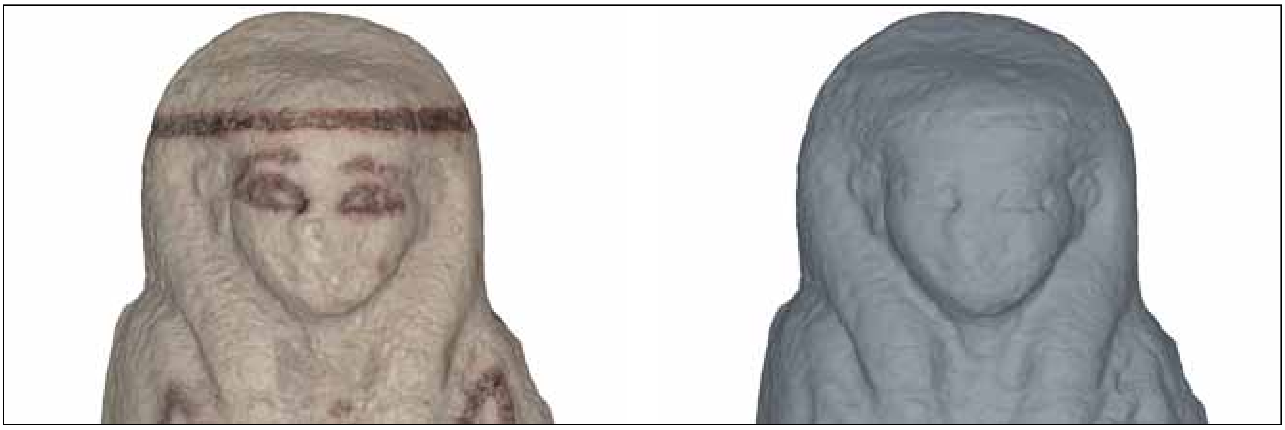

Fig. 8: 3D model created by laser scanning with and without colour. UC29999A © The Petrie Museum of Egyptian Archaeology, University College London.

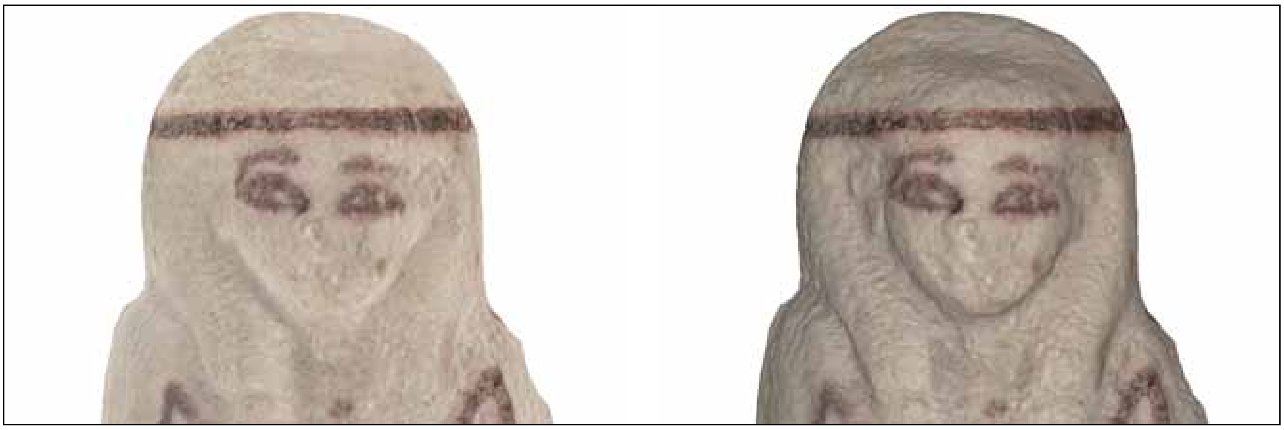

Fig. 9: 3D model created by laser scanning artificially lit with different directional light. UC29999A © The Petrie Museum of Egyptian Archaeology, University College London.

lar enhancement and diffuse gain where appropriate. This means that PTM can be used to derive a single, customized, informative image of an object, which can be used for documentary purposes and in printed archives (Mudge *et al.* 2005: 3–9). Moreover, provided that the electronic PTM is retained, this can be adjusted at a later date if necessary.

A significant complication surrounding increased employment of all of these techniques is the size and type of image files created. To some extent, cloud-based storage may help to resolve issues relating to file size and space for back-up systems. However, there are numerous, ever-changing file types in use. Any conservation information stored in computer data files must remain easily accessible in the future. This necessitates greater importance to be assigned to data preservation, a branch of conservation that must develop alongside digital imaging techniques.

Implications For Preservation And Accessibility

Appropriate conservation requires a balance to be struck between preservation and accessibility (ICOM-CC 2008: 1). The application of digital imaging technologies to object conservation must be implemented such that an acceptable balance is achieved.

There is a range of positive effects on object preservation that can be brought about by extending use of digital imaging techniques, including:

- Greater understanding of object surfaces.
- Reduced need for conservators to handle objects e.g. use of images for condition assessments and for comparative assessment pre- and post- loan.
- (Almost) risk-free loans: loans of object in 3D digital form.
- Interactive in-house electronic displays: allowing viewers greater accessibility to object features without risk to the original.
- Replicas produced by imaging and 3D printing present less risk to object condition than those made by moulding and casting. These may also be used in handling sessions rather than ‘real’ objects.

Concurrently, these can bring about positive effects on accessibility. (1) can allow greater intellectual accessibility to objects; (3) can extend the number and range of people able to view objects in detail by making them available in more settings; (4) means that viewers have a more thorough appreciation of objects than possible with traditional displays; (5) means that more ‘objects’ will be available for handling than would be possible if original objects were used, many of which would be considered much too valuable to allow handling by the general public.

The use of digital reconstruction can also help to resolve issues regarding restoration. If there are doubts concerning the original form of an object then digital restoration can be employed to demonstrate the different possibilities (Keene 1998: 25; Kalay *et al.* 2008: 5). This improves intellectual accessibility of objects to the viewing public: if physical restoration is used then one option must normally be selected. Similarly, if an object was subject to alterations during its pre-museum life, digital restoration may be used to illustrate the appearance of the object at each different stage without physically interfering with it.

It is evident that a selection process will be employed when deciding what and how to image (Keene 1998: 39); the neutrality of such images can be questioned (e.g. Kalay *et al.* 2008). However, traditional exhibitions also select particular objects from a museum's collection and display them in a carefully considered, usually static manner. Such displays normally render at least part of an object visually inaccessible - the part judged least important by the curator. In this respect, digital images can be more neutral if the capacity to rotate and magnify the image is enabled. This puts more power into the hands of the visitor.

Use of accurate physical replicas has been a particularly contentious issue for many years. It is not currently in favour with most museums for a combination of reasons including issues regarding authenticity and value, as well as the costs involved (Zimmer *et al.* 2008). Reproductions have been criticized for failing to communicate, or even destroying, the uniqueness and significance of the original object (e.g. Benjamin 2008 [1936]). This is grave criticism, since preservation of significance is held as a responsibility of conservation (ICOM-CC 2008: 1).

Failure for a replica to completely convey intangible qualities of the original is inevitable; such models have not experienced the 'biography' of the original objects (Pye 2001: 64), which causes people to attach particular feelings and importance to them. The claim that replicas *destroy* the significance of objects is more severe, but unfounded provided that the replica is not a forgery made with intent to deceive. Replicas cannot possibly replace the significance of the original nor is that the point of them. The replica is created to improve (and disperse more widely) understanding of the original, which concern for its preservation may otherwise prevent. This can include physical handling of tactile replicas and use of digital models to reveal intangible qualities not possible in physical displays because of risk to the object and/or health and safety concerns. For example, PTMs may be developed to reveal the appearance of objects under different conditions of illumination, such as oil lamp light for medieval lustre ware (Bridgman and Earl 2012).

The importance of touch for understanding objects is increasingly being emphasized, particularly for groups including hospital patients, the elderly and the visually impaired (Dudley 2010; Edwards *et al.* 2006; Chatterjee 2008; Pye 2008; Noble and Chatterjee 2008; Rowlands 2008; Phillips 2008). Tactile replicas can help to extend these benefits when the originals are too fragile for handling and their use is supported by the recent conference resolution *In Touch with Art* (St Dunstan's and European Blind Union 2010: 11–12).

Potential Negative Implications for Accessibility

It is possible that greater introduction of physical replicas and digital 3D objects will lead to reduced sensory contact with original objects. Whilst tactile replicas may expand the range of objects available for visitor handling, use of these instead of original objects could mean that members of the general public never experience direct physical contact with objects. This is concerning for all museum visitors, but particularly for those with sight problems.

Many museums do have provision for general handling as well as specific programmes for the visually impaired. For example, the British Museum operates a handling programme for the visually impaired, a touch tour in the Egyptian Sculpture Gallery, and touch provision in the Parthenon Gallery (British Museum 2006: 11). However, it is clear that the selected objects are either considered relatively robust, or relatively minor items from the collection, as in the case of objects used at the British Museum's handling tables.

Overall touch provision within art and archaeology museums is sparse (Classen and Howes 2006; Dudley 2010: 11; Were 2008). This cannot be blamed entirely on museums. There is an expectation that objects should be cared for to enable current and future generations to appreciate them, which necessitates some restriction on direct contact with objects. In many cases, objects are so fragile that any handling by non-professionals would be highly inadvisable. However, since tactile contact with original objects is already limited, any replacement of current 'touch objects' with replicas would be very concerning. Where touch objects are used, they must be of adequate quality, which is not always currently always the case (Spence and Gallace 2008; Candlin 2003). For example, a plastic replica of a bronze or marble sculpture would be inadequate because it will not communicate important characteristics of the original, including weight and surface temperature.

Electronic loans presenting 3D objects mean that visitors have no direct contact with original objects at all. Their employment should be restricted to cases where objects are too fragile to travel, or for high-risk environments such as schools, which would not normally benefit from any sort of object exhibition.

Use of such electronic displays in-house may risk encouraging poor display of original objects, or no display at all. If digital exhibitions enable visitors to view objects from all directions under different lighting conditions then it may become tempting for conservators to leave originals in storage for longer periods of time, or for those on display to be lit at lower levels to preserve them for longer. It is important that these advanced images of objects are carefully designed into museum exhibitions in order to enhance displays, not to substitute proper display of physical objects. It may be possible to build conservation benefits into such displays. For example, staggered lighting may be used for dramatic effect; the digital image may first be presented together with a supporting text caption, followed by illumination of the object. This would only be suitable for special exhibitions or for a few objects within a gallery due to the costs involved and the fact that waiting for the object illumination could become tiresome. A similar approach (without the use of digital images) has been employed for the Ardabil carpet at the V&A, which is illuminated for ten out of every thirty minutes.

Conclusions

Taking into account the advantages and limitations of the techniques, CT scanning is best used on the current ad hoc basis (together with specialist centres to which objects can be sent for imaging) until the developments being tested by the EDUCE project reach a more mature stage, at which point its role should be re-evaluated. 3D laser scanning and PTM are best used for two separate areas: PTM for creating interactive, high-resolution images of objects to document surface features and condition; and laser scanning for creating accurate 3D models of objects, to be used as digital records of artefacts and allow viewing from different angles. For quantifying loss over time in addition to observing changes in condition then it is best to use PTM in conjunction with laser scanning. Both techniques can be successfully used for interactive electronic exhibitions either online or in museums.

Inevitable, cost plays a significant role in determining the chosen imaging technique in any given situation. PTM offers significant advantages over standard digital photography and in some areas over laser scanning; it is considerably cheaper than laser scanning and only somewhat more expensive than digital photography. The starter kits produced by CHI make the technique reasonably accessible and potentially feasible for use even in small museums with limited budgets and access to computer specialists.

Therefore, PTM constitutes a practical, affordable means of creating images useful for conservation purposes. Laser scanning has undeniable value but the equipment involved is simply out of reach for most small institutions; these may continue to commission work when deemed necessary from places like the Liverpool Conservation Centre. Consequently, PTM in particular is a highly significant technology with the potential to become even more important.

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