3D SCANNING AND REPLICATION FOR MUSEUM AND CULTURAL HERITAGE APPLICATIONS

MELVIN J. WACHOWIAK AND BASILIKI VICKY KARAS

ABSTRACT—The recent proliferation of commercial three-dimensional digital scanning devices has made 3D scanning, and virtual and physical replication, a practical reality in the field of heritage preservation. 3D scanning produces a high-precision digital reference document that records condition, provides a virtual model for replication, and makes possible easy mass distribution of digital data. In addition to research, documentation, and replication, 3D data of artifacts are increasingly being used for museum collections storage and packing designs. The cost and complexity of 3D imaging technologies have made 3D scanning impractical for many heritage institutions in the past, but this is changing, as an increasing number of commercial systems are being tailored and marketed for heritage applications. This paper presents a review of the current state of 3D imaging in the cultural heritage field, methods of physical replication, the different systems used in heritage applications, criteria for choosing a system, and the techniques used for working with the data. Attention is given to identifying those objects that are not likely to be suited for 3D scanning.

TITRE—Techniques de balayage et de reproduction en trois dimensions pour applications muséales et culturelles RÉSUMÉ—La récente prolifération sur le marché de méthodes électroniques de balayage en trois dimensions (3D) a fait en sorte que le balayage et la reproduction, soit physique ou virtuelle, sont maintenant applicables de façon pratique dans le domaine de la préservation du patrimoine culturel. Le balayage en 3D produit des données électroniques de référence de haute précision qui peuvent documenter l'état de l'objet et permettre de produire un modèle virtuel à fin de reproduction. La saisie de données sous mode électronique (digital) permet aussi de les diffuser facilement et à grande échelle. En plus de faciliter la recherche, la documentation et la reproduction des objets, la documentation en 3D des objets sert de plus en plus à améliorer le design des systèmes d'entreposage des collections muséales et celui des caisses de transport. Auparavant les technologies d'imagerie en 3D étaient trop coûteuses et complexes pour beaucoup d'institutions muséales, mais ceci n'est plus le cas présentement, alors que de plus en plus de systèmes commerciaux d'imagerie en 3D sont développés spécialement pour des applications muséales ou culturelles. Cet article présente une revue de l'imagerie en 3D couramment appliquée dans le domaine du patrimoine culturel, des méthodes de reproduction physique qui existent, des divers systèmes utilisés dans le domaine patrimonial, ainsi que les critères de sélection pour de tels systèmes et les techniques qui sont utilisées pour manipuler les données. Les types d'objets qui ne sont pas typiquement de bons candidats pour le balayage électronique en 3D sont identifiés.

TITULO—Escaneo en 3D y replicación para museos y su utilización en patrimonio cultural RESUMEN—La reciente proliferación de dispositivos comerciales de escaneo tridimensional (3D) ha hecho que el escaneo en 3D y la replicación virtual y física sean una realidad práctica en el campo de la preservación del patrimonio. El escaneo en 3D produce un documento de referencia digital de alta precisión que registra la condición, produce un modelo virtual para replicar y hace posible la fácil distribución en masa de los datos digitales. Adicionalmente a la investigación, documentación, y replicación, los datos en 3D de los artefactos están siendo utilizados cada vez con más frecuencia para diseñar el almacenamiento y empaque de las colecciones de museos. El costo y complejidad de las tecnologías de imagen en 3D ha hecho que el escaneo en 3D no haya sido práctico en el pasado para muchas instituciones de patrimonio, pero esto está cambiando a medida que un mayor número de sistemas comerciales están siendo diseñados y mercadeados a la medida para aplicaciones de patrimonio. Este artículo presenta una revisión del estado actual de la creación de imágenes en 3D en el campo del patrimonio cultural, los métodos de replicación física, los diferentes sistemas utilizados en aplicaciones patrimoniales, los criterios para seleccionar un sistema y las técnicas utilizadas para trabajar con los datos. También se menciona la identificación de aquellos objetos que muy probablemente no se prestan para escaneo en 3D.

TÍTULO—Escaneamento 3D e duplicação para aplicações em museus e em patrimônio cultural RESUMO—A recente proliferação de aparelhos de escaneamento tri-dimensionais (3D) digitais tornou o escaneamento 3D e a duplicação virtual e física uma realidade prática no campo da preservação do patrimônio. O escaneamento 3D produz um documento de referência digital de alta precisão que registra a condição, proporciona um modelo virtual para duplicação, e torna possível a fácil distribuição em massa de dados digitais. Além da pesquisa, documentação e duplicação, os dados 3D de artefatos têm sido amplamente usados para armazenamento de coleções de museus e designs de embalagens. No passado, o custo e a complexidade das tecnologias de obtenção de imagens 3D tornaram o escaneamento 3D impraticável para muitas instituições de patrimônio, mas isso está mudando, uma vez que um número crescente de sistemas comerciais estão sendo desenvolvidos sob medida e comercializados para aplicações em patrimônio. Esse trabalho apresenta uma revisão do estado atual da obtenção de imagens 3D no campo do patrimônio cultural, dos métodos de duplicação física, dos diferentes sistemas usados nas aplicações em patrimônios, dos critérios para escolher um sistema e das técnicas usadas para trabalhar com os dados. Também se tentou identificar aqueles objetos que não são passíveis de se adaptarem ao escaneamento 3D. A intenção do autor é fornecer orientação para os profissionais de patrimônio que estejam interessados em usar contratos de serviços de escaneamento ou que estejam pensando em adquirir equipamento.

1. INTRODUCTION

Three-dimensional digitization (also called 3D imaging or 3D scanning) is assuming an important place among documentation and analytical techniques used for cultural heritage objects (Zheng and Zhong 1999; Fowles et al. 2003; Mohen et al. 2006; Beaubien et al. 2007; Schaich 2007). Conservators from the Smithsonian Institution's Museum Conservation Institute (MCI) scanning program have worked over the past three years to incorporate 3D imaging in the conservation and research documentation of an object. This effort sought to explore—and in part, demystify—3D technology for other heritage professionals. 3D scanning neither replaces nor is fully comparable to photography, structural imaging such as radiography, computed tomography (CT scan), colorimetry, and other measurement techniques. It does, however, share many of the attributes of these techniques. It should logically be a part of the digital record of collections for documentation, research, and public accessibility.

3D scanning systems are relatively new, highly precise measurement tools. These systems provide a high quality, high-resolution 3D archive of an object's surface topography with measurement accuracy to the sub-millimeter level. In addition, 3D scanning allows measurement of the surface geometry, texture (which, in the jargon of 3D surface imaging, includes color), and volume of most objects, without contacting an object's surface. As in two-dimensional photography, a graphic representation of the surface is created. The 3D data provide an extremely accurate record of an object's physical structure, unlike flat photographic representations of objects or virtual reality displays of objects created by compiling 2D photographic images. Like photography, 3D scanning does not provide information about structure below an object's surface. 3D data, however, can be used in conjunction with x-radiography and CT scanning as a complement to these analytical tools to reveal structure and spatial relationships with very high resolution. For instance, a 3D scan image can be digitally combined with a radiograph to create a "pseudo-CT" image. A 3D scanner that captures object color adds yet another dimension to research and documentation; that is, it creates a virtual surrogate. While the CT scanner will provide internal structural information, 3D scanning generally provides higher resolution, and the object's size or location is not usually a restriction.

The purpose of this paper is not to compare the available 3D technologies, but to provide examples of choices made by MCI to build an in-house scanning program to complement other systematic documentation of collections and heritage material.

2. CURRENT STATE OF 3D SCANNING

In 2004, the MCI purchased a 3D scanning system not designed specifically for heritage applications. This imaging system, a portable, hand-held laser line scanner, was part of a pilot test to determine the applicability and usefulness of 3D digital recording for heritage applications (Beaubien et al. 2007). At the time, a survey of current literature and research on the topic of 3D scanning revealed very little information from the perspective of the heritage professional. Commercial providers hired by museum or heritage organizations to scan artifacts, architecture, or in situ monuments generally had produced what little literature existed. Even these were limited to short blurbs on Web sites used to promote a specific commercial scanning company, or to a cursory mention in heritage conference notes. It was clear at that time that there was a paucity of North American publications on the topic of 3D scanning for the heritage field.

In contrast, European professionals have been experimenting and reporting on their 3D scanning projects for a number of years (National Museums Liverpool n.d.; Virtual Heritage n.d.; Cooper et al. 2007). This European leadership in 3D documentation is often attributed to the sheer volume of historic sites and antiquities throughout Europe that need recording. Even though European professionals have been more public about the adaptation of 3D scanning into their repertoire of documentation and analysis, the reports often come from the technical research institutes or commercial companies hired to carry out the actual scanning and the data processing.

The lack of reporting from heritage professionals using 3D scanning for documentation and analysis is not surprising; 3D scanners are not usually part of documentation protocol. Until very recently, it did not make a lot of sense to invest time, money, and training in this new, rapidly evolving technology. In a North American context, 3D scanning of cultural material continues to be new and largely uncharted territory. Scanning projects undertaken, however, have shown that there is an enormous potential and interest for the application of 3D scanning in museum conservation and heritage preservation (Logan et al. 2005; Boulton 2007; Powell 2007).

The success of heritage 3D scanning projects has resulted in the recent expansion in commercial 3D technology designed with an eye to heritage applications. Most commercial 3D scanning systems are designed to be used in the computer gaming or movie industry, or as a precise measuring tool for industrial applications and reverse engineering. Unlike in the heritage field, commercial and industrial applications do not typically require color information, nor do they consider the detailed and complex geometric surfaces that objects possess. The museum or heritage object introduces a number of challenges to the 3D scanning process, which in the past made scanning the object difficult and processing the data time consuming, ultimately producing an unsatisfactory result.

3. PRACTICAL USES FOR 3D SCANNING

The immediate benefits of 3D scanning include virtual examination and research. The objects can be brought into the virtual workroom, and there is essentially no impact on the object's physical integrity. But there is much to be gained beyond this.

Industrial and research applications for 3D scanning include quality control and reverse engineering. These are analogous to documentation and replication activities in cultural heritage work. During quality control, parts and assemblies are compared to the design specification and checked for tolerances. In heritage work, documentation of the surface and volume of an object would be an end unto itself. However, comparisons of a set of objects are only now being explored. In this type of research, the identity and origin of a set of objects is compared to known works. A set of features can be compared, or an entire volume of objects can be assessed. A good example is found in the recently published Matisse sculpture research (Boulton 2007). For this research, several bronze, plaster, and terra cotta pieces were fully scanned and virtually compared. In the past, calipers and other tools would have been used to carry out this kind of analysis. The opportunities for creating multiple cross sections and 3D overlay of data would not have been possible without 3D scanning. The Tate Modern in London has scanned cellulose nitrate sculptures by Naum Gabo in order to document the objects before the degrading plastic disintegrates. 3D scanning is also being used to construct replicas of the original shapes of these severely distorted sculptures (Morgan et al. 2008).

Reverse engineering is essentially the process of discovering the materials and technologies used to create a device. In industry, this often includes disassembly of mechanical devices for replication of parts and functionality. For heritage purposes, this might be akin to chemical analysis and replication by mold making. Now, using 3D scanning and fabrication, it is possible to recreate whole objects or portions of an object. For example, restoration of missing parts too delicate to be molded can be accomplished by scanning. In one interesting Smithsonian project, a plaster piece mold has been scanned to replace lost pieces, as well as to create a "cast" from the mold. The scanning was completed in a few hours with minimal handling of the parts during scanning. Creation of replicas for study is now possible at any scale, and in almost any material. Replicas are valuable from research, exhibit, and restoration perspectives, and they can enhance the general public's appreciation of the museum or heritage site. Scale models and surrogates can be handled to provide an excellent tactile experience.

Adapting approaches commonly found in industry can enhance collection care. Tools used in industrial prototyping, package design, and architectural planning will no doubt contribute to more efficient packing, object movement, and exhibit design (Gallup and Harlow 2006). Using 3D scanning data, packing materials can be custom cut to fit objects, movement and space utilization can be planned, and mounts can be fabricated more effectively.

Most scanners produce object data of accuracy and resolution beyond the ability to practically replicate them, in physical form, by any of the standard methods. Replication devices, such as computer numerical controlled milling machines and 3D printers (rapid prototyping), are not generally capable of maintaining this resolution in the final product. The term resolution applied to replication refers to the ability to accurately produce an object from the scan data. Closing the gap between scanning and reproduction resolution is the fastest improving area of commercial reproduction methods.

Computer-aided design and computer-aided manufacturing (CAD/CAM) are now the norm in commercial product design and development. 3D scanning is used in the commercial cycle of development, testing, verification, and reverse engineering. Increased demand for products is effectively bringing down the cost of specialized replication work. Scanning for heritage is similar to commercial scanning in that constraints based in the scanning and production are recognized, and useful as planning tools. Some heritage applications do not require the highest level of execution, and perfect replicas are difficult and expensive to attempt. Faithful reproduction of the production part is limited by the high cost of fabrication, as well as by technical constraints of any method. Knowledge of what is desired, what is achievable, and at what cost will inform selection of materials and methods.

The level of resolution and choice of material determine the final cost of the replica. In direct production using catalyzed plastics or powder and binder systems (often collectively known as rapid prototyping), the resolution is quite variable. For machined parts, the tool diameter and the nature and extent of undercuts limit resolution, yet both production methods can yield nearly identical results. Again, understanding the constraints of the replication technique may be only a part of achieving the desired result.

Beyond resolution or choices of material, there are two additional practical limitations on fabrication of objects from 3D data. One is certainly the obvious difficulty in reproducing color and appearance. The second is the size of a single part that can be made by any fabrication technique. Most methods will produce a single object no larger than 0.75m × 0.75m × 0.5m tall. For larger dimensions, the final object will generally need to be built from pieces. This too will probably change in response to need arising in the commercial market. Parts can be produced as positives or negatives, resulting in the desired product directly or indirectly; for instance, a mold can be made directly from scan data. Digitized object data can easily be scaled smaller or larger, and therefore can be used to produce scaled replicas.

It is not difficult to imagine the use of replication techniques in attempts to create forgeries. Familiarity with the strengths and weaknesses of the various methods, as well as new developments, is advisable.

3.1 STEREOLITHOGRAPHY

The term stereolithography is generally applied to all forms of direct reproduction of parts. The terms stereolithography, rapid prototyping, and 3D printing are synonymous. Most often, stereolithography refers to the polymerization of photocurable resins to produce a part in a stepwise manner. The machine is also referred to as a stereolithography apparatus, or SLA. (Confusingly, the abbreviation SLA is also used to describe the method or the part produced by the machine.) While it has entered the vernacular, SLA is a registered trademark of 3D Systems, one of the pioneers in the technique and machinery to produce 3D solid forms.

SLA produces an object in an additive way. Software divides a 3D model into slices and assists in the orientation of the part during the build and creation of supports; similar to armatures, these supports are

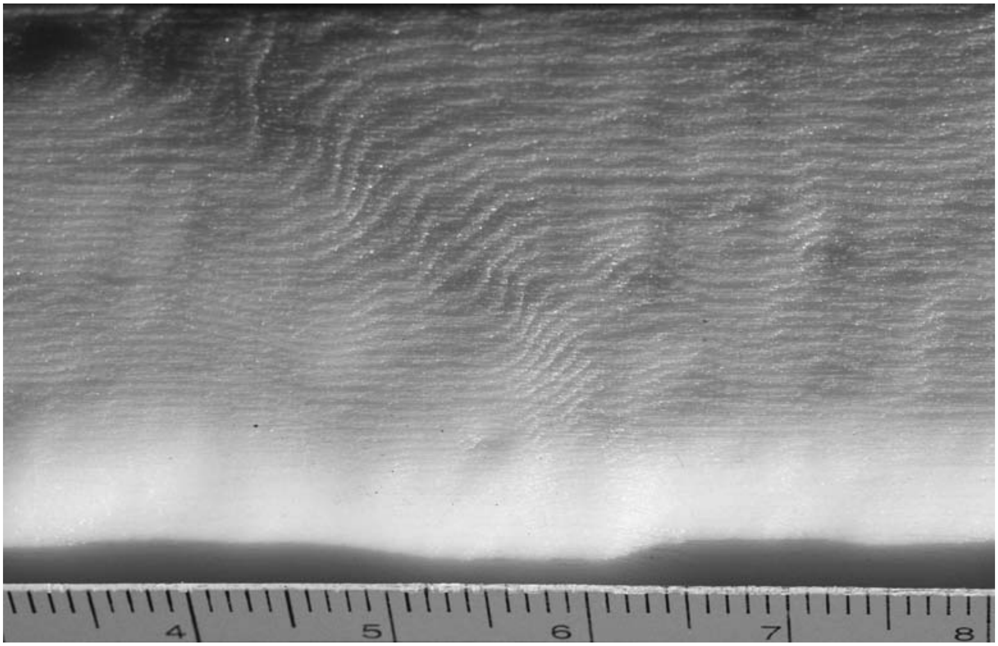

Fig. 1. SLA build lines visible on near-vertical (perpendicular to build axis) surface of Mongolian stone sculpture replica. Scan data was collected from sculpture on location in Mongolia. Scale in millimeters; replica printed at 75% scale.

removed by hand later. The replica is built from the bottom up in a vat of resin (often acrylic or epoxy). A light beam (usually a UV laser) cures a layer, moving over the surface much as an ink-jet printer moves over paper. Then the platform that supports the replica is lowered just below the resin surface, and a new layer of resin is added. For lower resolution models, the resulting "build lines" can sometimes be seen more easily as stepped levels (fig. 1). Even higher resolution models can show some steps. Finally, uncured resin is washed from the part and the supports are removed by hand.

There are currently some other weaknesses in stereolithography methods, in addition to size restrictions and resolution. Beyond the dimensional limits imposed by the size of resin vat, there will also be weight limits for the platform. Therefore, large objects will need to be hand assembled from smaller SLA parts. While the term rapid prototyping is used, moderately sized objects can take several hours or more than a day of machine time. The greater the resolution of a part, the more time—and cost—required. Moreover, the chemical stability of some of the resins needs to be carefully considered. There are many resin types available; including some designed for use in making pattern masters or high temperature test models. This suggests some durability of materials, but only from a commercial standpoint. Of course, the color of the object produced will be the solid color of the resin. Currently, there are few devices that can produce naturalistic color.

Metal parts can be produced by a method similar to stereolithography, in which layers of metal powders are built up and bonded together by wax or resin, and then sintered in an oven. In some cases, the space occupied by bonding agent is filled by molten metal such as brass. Very durable models, dies, or molds can be made this way.

The strengths of these methods are that accurate replicas can be quickly produced without mold making and they can be very accurate. The process is additive, therefore, thin walls, undercuts, and intricate detail can be easily produced. In fact, it is possible to easily produce loose, floating, and even moving parts, captured by their surrounding matrix. Production time and cost of rapid prototyping compares favorably to traditional mold making and casting. The cost of ownership of the SLA, however, is prohibitive for all but specialized service providers. Promotion of the development of the quality and color

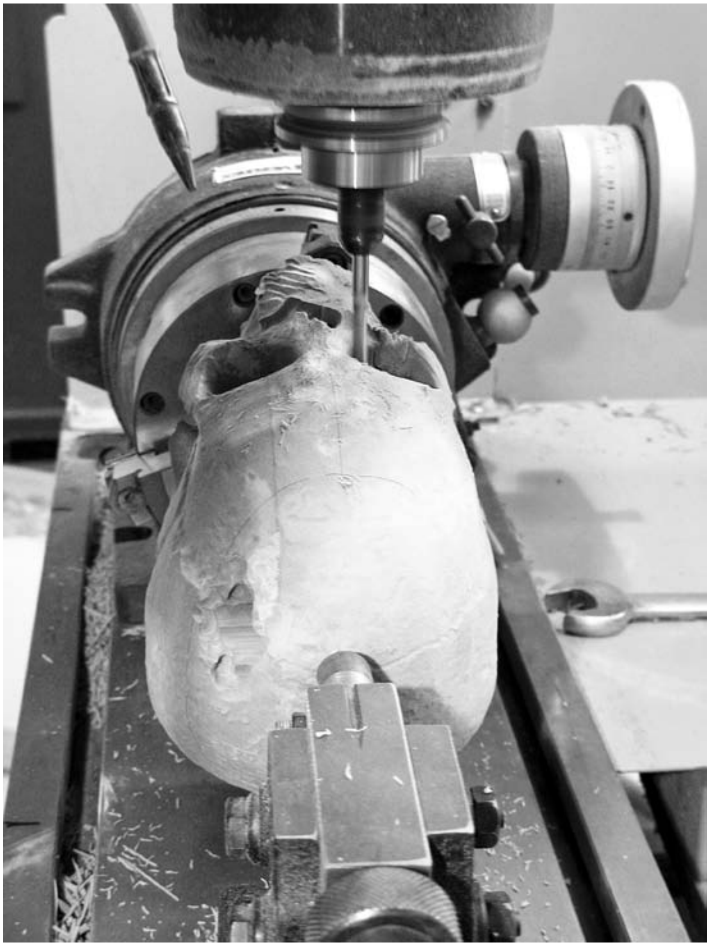

Fig. 2. CNC milling of replica of 17th century human skull from an archaeological site, part of a forensic reconstruction of the individual for a museum display (By Carolyn Thome, Office of Exhibits Central, courtesy of Smithsonian Institution)

reproduction from SLA equipment for heritage applications is an area for which conservators are ideally suited.

3.2 COMPUTER NUMERICAL CONTROL MACHINING

Computer numerical control (CNC) machining is the method of controlling a cutting machine, usually a lathe, mill, or router. In each case, CNC cutting is a subtractive method in which the volume of material is reduced to create the final object. At its most basic, this is usually a multi-axis vertical milling machine (fig. 2). CNC milling instructions include movement of the stock and cutter on, at minimum, x, y, and z axes (3-axis milling). A 5-axis mill can also move the spindle axis to cut very complex shapes. In some cases, such as a part finished on all sides, the stock must also be repositioned during cutting. Typically, the cutters are changed automatically so that after rough cutting, smaller diameter cutters are used to produce details. The ultimate resolution is determined by the edge radius of the last cutter used, and the step resolution of the CNC axis control. Naturally, the physical properties of the material being cut will differ, and therefore, will affect the resolution. Color cannot be a practical part of CNC milling operations because of the subtractive nature of this process and the limited choices in stock materials.

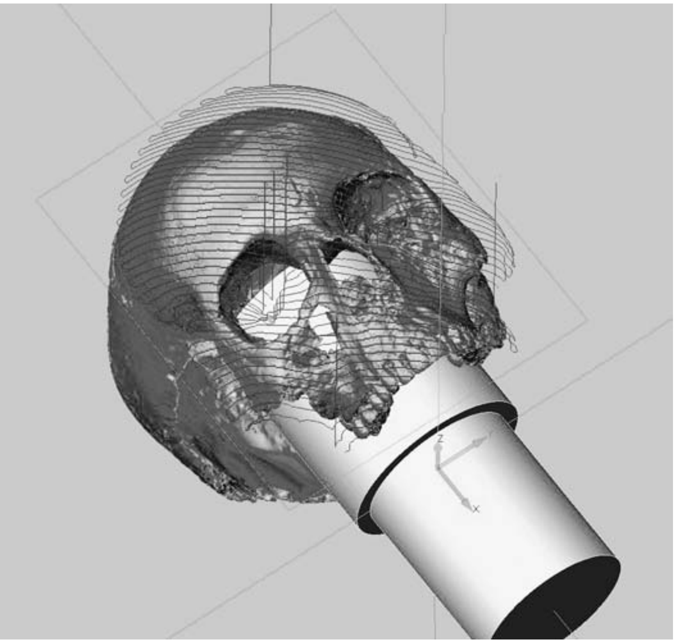

Fig. 3. Screen image depicting CNC tool paths for creating replica seen in fig. 2. Lines indicate best entry point, cutting paths, and exit point for each cutting tool used to replicate the human skull (By Chris Hollshwander, Office of Exhibits Central, courtesy of Smithsonian Institution)

The wide range of materials that can be used for milled reproductions is a strength of this technique. Milling can be done in ferrous and non-ferrous metals, wood, plaster, and many types of plastics. It is very time-consuming (and therefore expensive) to produce thin-walled parts. Doing so requires cutting sections that may have to be joined later to produce a hollow object. Producing undercuts in complex shapes is limited by the cutter's access to these areas; in some cases, they simply cannot be reached.

Scanners save data in formats that can be read indirectly by CNC software (fig. 3). The creation of cutting paths and tool selections are part of the work of the specialized operator. Of course, a deep understanding of computer control methods and stock materials is required. Again, the cost of a CNC milling machine is prohibitive for all but specialized service providers.

CNC routing is closely related to CNC milling, and is good for those objects that can be made from plank-like flat stock. CNC routing is 3-axis milling and is adequate for lower resolution, smaller z-axis parts on the order of 6 in. (15cm) in size. Larger sizes can be made by CNC routing, even up to a 10 × 30 ft. In addition to producing large parts, routing can produce replicas from foams and rubber materials. As with CNC milling, color cannot be built into the part at this point in time.

3.3 STABILITY OF MATERIALS

Raw materials used for reproduction are most often intended for a commercial purpose, not for an archival record, and may be quite variable. The necessary service life of a commercial model or test part is very short compared to that desired for most heritage applications. Some parts may be durable, but other materials will be predictably short-lived. These less durable materials would be best used as models or precursors to final objects. There are some very robust materials used for aerospace or deep-sea applications that that might be excellent choices for long-term needs. A thorough understanding of the purpose of the replica from the outset will provide the best guidance, because materials and their properties are so variable. Ultimately, the scan data is probably a far better archival resource. Of course, one must consider backing up files, archiving, migration of data, and other factors associated with all digital preservation.

Fig. 4. Breuckmann triTOS-HE structured light scanner on tripod head, showing projector and camera components, with 10cm sensor bar between

4. OVERVIEW OF THE 3D SCANNING SYSTEM

Conceptually, the design of most scanners is straightforward. In heritage work, one or more technologies may be used but laser and white light scanners are the most popular. This is likely resulting from their lower cost ($100,000–$200,000), accuracy, and reliability. Triangulation systems, in which three reference points are used to compute the distance of any point on the surface, provide a good model for describing the basic principles of 3D scanning. The Breuckmann triTOS-HE, shown in figures 4 and 5, has many external components common to triangulation systems:

- The projector, camera, and general working distance are fixed. In the configuration illustrated, the bar between the camera and projector is small (10cm), and resolution is very high (60μm)
- A series of patterns is projected on the surface of an object (fig. 6)
- The camera records the changes in the shape of the patterns
- Image analysis is done in the PC software, and within seconds, the result is shown as the portion of the surface within the field of view

Most commercially available 3D scanners designed for scanning heritage objects are portable

Fig. 5. Breuckmann triTOS-HE structured light scanner in use, 20° triangulation. Lower point of triangle represents one of a million points typically collected in this 10cm field of view. Object is identified in fig. 9

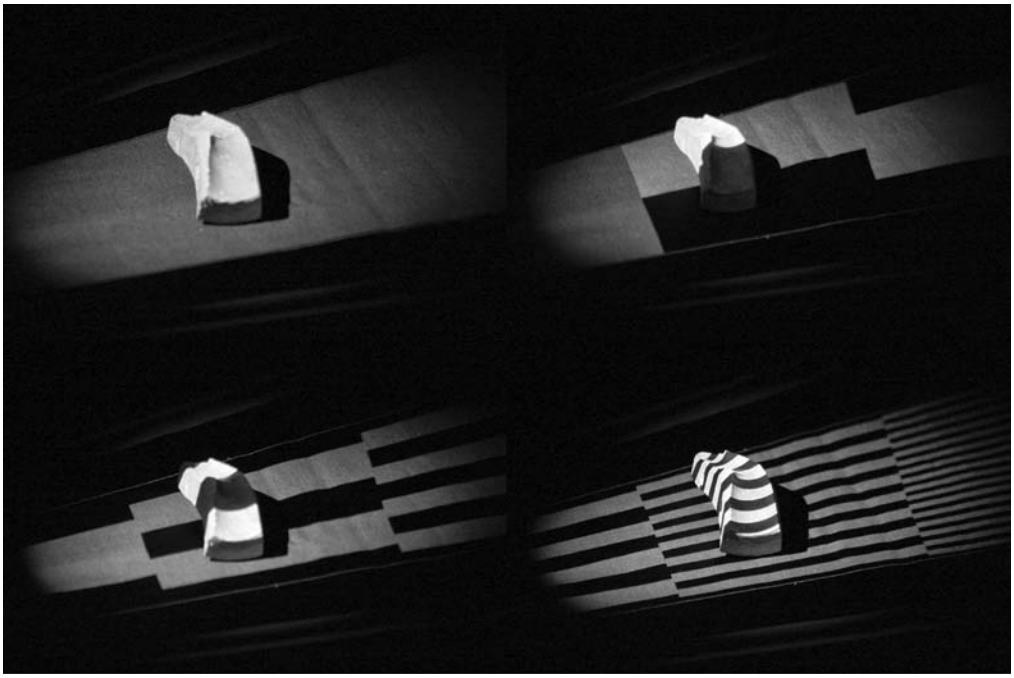

Fig. 6. Sequential patterns projected by structured light scanner on the surface of the object (portion of a plaster piece mold by Hiram Powers, catalog no. 1968.155.173; Smithsonian American Art Museum). Scan data will be used to replicate the mold, replace lost pieces, and to create a "cast" based on negative space calculation

systems mounted on tripods, with small to medium (<10m) range requirements. The most common range systems are structured (white) light and laser triangulation scanners. Both laser and white light scanning are excellent surface-recording tools and most types are capable of color capture. Their limitations lie in what they can "see," meaning both the light source and sensor (the camera) must have a clear view of an object's surface. Objects that have deep undercuts, highly reflective surfaces, or significant subsurface scattering (like marble or jade), are difficult to scan with triangulation scanners.

In structured light scanning, a sequence of organized patterns of light (for example, grids, dots, or stripes) is projected onto the scan subject, and the deformation of the pattern on the subject surface is analyzed. The scanning system's camera is specially aligned with the light projector, and simultaneously records the distortion of the light patterns (fig. 6), and uses a complex algorithm to calculate the distance of every point (Zhang and Huang 2006). Data can be acquired very quickly at the rate of about 1 second per view. Because the spatial data and RGB color values can be recorded together, the color information is registered exactly with its corresponding coordinate (*xyz*) point. The precision of this spatial registration is highly desirable in cultural heritage work.

Laser scanners record 3D point locations through the principles of triangulation by projecting a low-intensity laser spot or laser line onto the scan subject, and recording its reflection back to the scanner using a camera (sensor). Just as with white light scanning, the laser source and the camera must be in fixed positions relative to each other (Bernardini and Rushmeier 2002). A laser in low to medium range is low wattage visible light, but this should be verified in each case. Some laser systems use red, green, and blue lasers to capture color.

Some specific optical properties can create problems with all non-contact scanners. Extraneous reflections from highly reflective surfaces such as polished metal are an example of stray light that interferes with good surface recordings. In industry, these surfaces are sometimes coated with matte spray to reduce reflections. Light-absorbing surfaces, particularly very dark ones, also sometimes create problems.

Sharp edges may not scan well. Translucent or transparent materials such as glass and plastic will also be difficult to scan. Naturally, objects that change shape when handled are problematic with most systems. Examples would include those that have movable parts or no fixed supporting structures, such as costumes, inflatable structures, feathers, fur, hair, and rubber.

Where color capture is desirable, environmental lighting takes on as important a role as it does in photography. Whereas data capture without color information improves with low or no ambient lighting, data with color requires attention to lighting the object. At the time of this writing, advances in the color capture of commercial 3D scanning systems are producing reasonably accurate color data. However, the success of accurate color capture continues to depend on the ability to control the ambient and directional light on an object during scanning, which can be difficult to manage.

5. CRITERIA FOR CHOOSING A SYSTEM

Beginning in 2004 with a scanner designed for industrial and commercial applications, MCI conservators were faced with the challenge of marrying the 3D documentation capability of this scanner with the exceedingly high standards of archival documentation carried out by heritage professionals. Although many commercial 3D systems claim resolution to the submillimeter, a textured object with complex geometry poses many problems for a scanner originally designed for industrial applications. An object's multitude of surface detail in the form of pits, cracks, bumps, accretions, abrasions, and losses is the critical identifying fingerprint of its condition. The raw data collected by scanning is composed of the millions of data points that captured the surface detail. Often, however, the post-processing system software used in many scanners to produce a 3D graphic model from the raw data is not able to handle such large data sets. The raw data is thus routinely compressed or "decimated" (mathematically reduced by set amounts) during post-processing to make it a smaller, more manageable size. As a result of this reduction, detail is often compromised, and the final 3D graphic view of the object appears smoothed and gives the object a plastic or waxy appearance. In most cases this outcome is unacceptable to the heritage professional.

It was clear to the MCI conservators at the end of the trial period with the industrial laser scanner that for the marriage between 3D scanning and the high standards of the heritage professional to work, it would require a heritage-tailored scanner that could handle the unique material and geometry of heritage objects. In the spring of 2006, MCI purchased a structured light 3D scanner (also called a white light scanner), purpose built for heritage applications. The switch by MCI from a commercial laser scanner to a purpose-built heritage structured light scanner was determined by the system's suitability to the applications at MCI, the attention paid by the scanner manufacturer to the nuances and demands of heritage scanning, and the manufacturer's commitment to fine-tuning their system and software to work with heritage documentation and conservation.

When the decision was made to purchase a second scanner for MCI, the obvious priority was to choose the best system for heritage applications. As there are several scanners now on the market that advertise heritage applications, it is important to keep in mind the desired end result in terms of a system's resolution and data processing capability. Other important factors to consider are how and where the scanner will be used, for example, whether or not the potential scanner will be able to operate in a small workspace or withstand frequent transportation to scan indoor and outdoor objects. Boehler and Marbs (2002) outline several considerations for selecting a scanner for heritage applications; some of their broad organizational headings are useful.

5.1 ACCURACY, RANGE, AND RESOLUTION

Accuracy is described by Bernardini and Rushmeier (2002, 151) as a "statement of how close the measured value is to the true value." A manufacturer's statements of a scanning system's accuracy (or statements of its precision) are based on tests used for length measurement developed for coordinate measurement machines or surveying applications. Since measurement error increases with distance between the scanner and object, the accuracy of a scanner depends on the size of an object and the working range of the scanner.

Boehler and Marbs (2002) also suggest three ranges of heritage scanners based on the widely variable sizes of heritage objects. For small objects, scanners in the small range category, from 0.1 to 1m, would be most accurate at capturing surface detail. For medium sized objects, there are scanners with ranges from 1 to 10m, and for very large objects, other scanners with ranges from 10 to 100m. A small range scanner can typically have a single point accuracy of 0.1mm and less for objects scanned up to 1 m working distance. In comparison, a medium range scanner can have a single point accuracy of 0.5mm at 2m and 2mm at 10m. Interchangeable lenses will result in different ranges for the same scanner. Specifications of scanner range, however, are the manufacturer's best-case scenario. Most often working range, and thus accuracy and resolution, can be compromised by surface qualities of an object, such as reflective material properties, and by environmental interference from ambient light. Resolution refers to "the smallest distance between two points that the instrument measures" (Bernardini and Rushmeier 2002, 151).

5.2 FIELD OF VIEW

Each system's field of view will vary; that is, changes in field of view result in changes in range. A system with interchangeable fields of view is ideal for heritage scanning. Changing fields of view during a single scanning project is beneficial for scanning an object that does not require data capture to the sub-millimeter for its entire surface. In these cases, areas of detail priority can be scanned with a smaller field of view while other less detailed or lower priority areas can be scanned with a larger field of view. This can be accomplished by using different ranges with the same scanner, or by using different scanners with different ranges and common data formatting. The data collected at different resolutions can then be merged. This selectivity leads to a smaller and more manageable data set without compromising the entire object documentation during data post-processing.

5.3 SPEED

The speed of a scanner refers to the rate of data acquisition measured in points per second. For most heritage objects documentation, a high point density is required for high resolution of surface detail, and most scanners can collect thousands or millions of points per second. "Points" refers to precise *xyz*-coordinates representing the object's surface. Related points form what is called a "point cloud."

5.4 REGISTRATION/ALIGNMENT OF DATA

Most objects will require multiple scans from several angles to capture an entire surface. With every scanning project, the individual scans must be registered or aligned in order to create a single 3D graphic model (Bernardini and Rushmeier 2002). It is very helpful to have a system in which registration and alignment of data takes place in real time while scanning an object. As each new scan of an object will likely be taken from a different angle or position, the operator must have a way to "piece" those scans together.

Targets are often used in industrial scanning projects on objects with little or no defining surface characteristics; targets easily detected by the scanning software mark regions of interest that are automatically assembled (Boehler and Marbs 2002). Other systems offer a turntable option designed to rotate at set increments controlled or recognized by the scanning software; the object is set on the turntable and scanned in the round while the software automatically pieces together each scan.

Both of these approaches to registration and alignment are ill-suited to most heritage object scanning. The target approach is undesirable because the object's surface may be compromised by the application of many small adhesive targets. The rotating turntable, while attractive for small objects, may not accommodate larger objects.

Contour matching is the third approach and one that is well suited to heritage object scanning. This method requires an overlap of data from one scan to the next. The human operator, viewing two overlapping scans on a split screen view on the computer monitor, can piece together the scans by selecting matching feature or contour points in the area of overlap in the images. The area of overlap should include perceptible features on the object's surface, such as cracks or bumps, that make contour matching easier as the 3D graphic image of the object is pieced together in a patchwork fashion. The contour matches do not have to be perfect, as the software responds to a close fit and rejects all but essentially perfect fits. Many systems on the market today will likely be capable of all three registration and alignment techniques.

5.5 IMAGING CAMERAS

Color information (also referred to as texture) is a highly desirable feature of heritage tailored scanners. Traditionally, color images were texture mapped onto the 3D graphic data in a post-processing step, which took place after scanning. Texture mapping (the fitting of images to surfaces, often with color and pattern) is still widely done, but is extremely time-consuming. There are some scanners that collect color data simultaneously with the geometric data (*xyz*-coordinates) so that each data point has its own color value attached to it. Most collect 8-bit RGB (red, green, blue) data, a smaller color space than current higher-end consumer photographic equipment. While the 8-bit color data will not supplant that from digital photographic systems, it is not meant to. With these scanners, it is possible to view the data with or without color information throughout scanning, as well as in the final product. The method and quality of color capture varies greatly among commercial scanners and if color is a desirable feature, it is important to thoroughly research the specifications reported by the scanning manufacturer.

5.6 EASE OF TRANSPORTATION

Ease of transportation becomes an issue for any planned off-site scanning where travel to the object or site is necessary. Most commercial systems designed for heritage use are portable, small, lightweight, and easily assembled and disassembled for packing and travel. Attention should be paid to how easily a system will break down into separate components for packing. Travel cases should be hard-shelled and durable enough to withstand a variety of transportation modes. Cases that are custom-fitted with protective foam so that a scanner system can be cavity-packed are available from some manufacturers and are highly recommended.

5.7 POWER SUPPLY

Most scanning systems can operate from batteries or generators in addition to a power line supply for outlets indoors (Boehler and Marbs 2002). There should not be a power supply issue for scanning systems working indoors in North America. If working off-site with a generator, it is recommended that a generator designed for powering precision equipment be used.

5.8 SCANNING SOFTWARE

Scanning system software should have easy-to-navigate interfaces for all scanning and processing windows (Boehler and Marbs 2002). Data collection and presentation on the monitor should be fast, and should offer different 3D graphic viewing options such as points, polygonal mesh, and solid views of the data. It is also highly desirable to have system software that accomplishes post-processing functions normally carried out in third-party software; this can be time- and cost-saving.

6. THE MCI HERITAGE SCANNING SYSTEM

After taking all of the above into consideration, MCI selected a heritage scanner that is portable and non-contact, and has the additional benefit of capturing color data, the triTOS-HE made by Breuckmann GmbH (Torentstrasse 14, Meersburg, Germany) (figs. 4, 5). Additionally, the system has a 20° triangulation angle, which improves the scanner's ability to capture data in areas of deep relief, and allows for fewer scans and better data capture on objects with complex geometry. In comparison, a scanning system with a greater triangulation angle might require several scans from varying angles to capture areas of complicated geometry. Interchangeable lenses and a central sensor bar allow the scanner three different fields of view (and ranges) from 10cm to more than half a meter. Because of the modular design, even greater customization is possible. The system software is also designed to process very large data sets in a series of easily navigable steps with a variety of additional options. Post-processing of data can be conducted on third-party software also supported by the manufacturer's representative.

A second purchase consideration was to establish relationships with the manufacturer and distributor that would continue beyond the initial purchase transaction. Although there are several choices of scanning systems on the market, it was important to have a commitment in place that ensured that operator, software, and hardware support were available for some time beyond the purchase date. The result is a mutually beneficial relationship that continues to develop

Lights properties

	On/Off	Edit
Light 0:	☑	●
Light 1:	☐	○
Light 2:	☐	○
Light 3:	☐	○

Color:
○ Ambient
● Diffuse
○ Specular

☑ Automatically apply changes to the scene

Fig. 7. Final 3D grayscale image, virtual lighting from one direction (object catalog no. F-1376 National Museum of Natural History, Smithsonian Institution). Small Mayan figurines were scanned to test feasibility of small object scanning.

between MCI, the manufacturer, and the regional distributor. With external support, a lab has the opportunity to stay current with new developments in scanning software and hardware, while at the same time providing the manufacturer with valuable feedback on scanning challenges presented by the unique nature of cultural material. Forging relationships such as these, however, is not usually the norm for large commercial companies. Cultivating relationships that extend beyond the purchase transaction is the responsibility of the customer and should be part of programmatic planning.

7. VIEWING THE VIRTUAL 3D MODEL

The best heritage-tailored scanner will be less effective without the proper tools to view and work with the 3D data; it is analogous to having the right camera with no way to process or view the image. Just as physical replication of 3D data is highly desirable for heritage professionals, study of the 3D data allows an unprecedented level of interaction with the final accurate and high-resolution images. Measurement of surface area, volume, point-to-point, and cross sectioning are a few early skills to master. Being able to rotate a virtual object easily on all axes and under different virtual lighting is a great advantage.

Software packages are available to communicate the results simply and in an environment that requires minimal training. Of course, there is a limit to what a minimally trained user will be able to do, but that should not restrict access and exploration of the 3D data. As more users explore and exploit the research potential of the data, there will be greater demands for, and new developments in use of this data.

7.1 COMPUTER NEEDS

The research and thought put into purchasing a 3D scanner should extend to the purchase of a suitable computer and, if needed, to third-party software, capable of processing the raw data and viewing final 3D graphic models. Commercially available computers with large memory capacity, fast processing speed, and excellent graphics display have become the norm

Lights properties

	On/Off	Edit
Light 0:	☑	○
Light 1:	☑	●
Light 2:	☐	○
Light 3:	☐	○

Color:
○ Ambient
● Diffuse
○ Specular

☑ Automatically apply changes to the scene

Fig. 8. Final 3D grayscale image, virtual lighting from two directions, same scan data as for the image in fig. 7

for today's technologically savvy world, and can be easily used for 3D scanning (Bernardini and Rushmeier 2002). A good example is a "gaming PC." This is good news for anyone thinking about purchasing a 3D scanning system or for anyone thinking about contracting with a commercial scanning company to do the work. Even if a computer is used only for viewing (which includes measurements and other surface analysis applications), as might be the case if scanning is contracted out, then the organization should have a computer dedicated to working with the final data produced by the contractor. This is equally important for in-house scanning programs, where it makes sense to have a computer dedicated to controlling the scanning system, and if possible, another dedicated to processing and viewing the 3D data.

7.2 LIGHTING AND THE VIRTUAL MODEL SURFACE

While two-dimensional photography is a valuable documentation and research tool, it requires that object lighting be carefully arranged to create depth cues or contrast, in order to inform the viewer or emphasize a condition. In some cases, lighting is purposely arranged to create a dramatic mood or to prompt an emotional response. Because 3D scanners map points in space only, there are no highlights or shadows recorded in the digital data and therefore the scanning process benefits from having low or no environmental lights. Even though color 3D data is highly desirable for cultural heritage applications, there are benefits to viewing the final data as a grayscale or monochrome 3D model. Virtual lighting can be added to 3D data and positioned in selected angles during viewing using the software, but only temporarily modifies the spatial data within that virtual context. The data is unperturbed by virtual interaction, so the "lights" can be moved or turned off to create a number of virtual lighting effects (figs. 7, 8). Likewise, color data can be turned off (figs. 9, 10), and false color elevation maps created.

Texture and texture mapping are terms used by metrologists and other scanning specialists in the same way that color specialists use the term "appearance." It

Fig. 9. Final 3D color image as scanned (Native American copper sheet object, catalog no. 200700.000 National Museum of the American Indian, Smithsonian Institution). Both sides could be imaged, lessening the need to turn over fragile objects

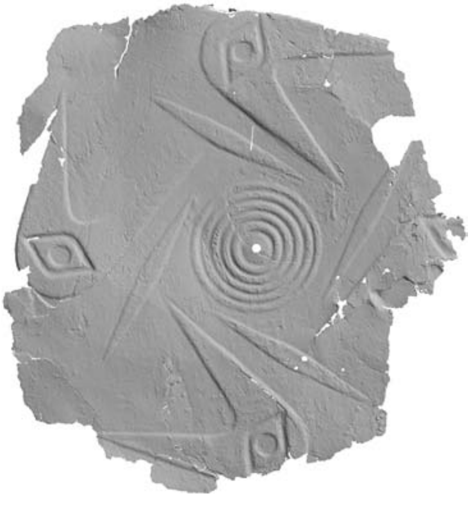

Fig. 10. Final 3D grayscale image, same scan data as for the image in fig. 9, with color "turned off"

becomes confusing to apply the word *texture* to a discussion about color documentation in scanning, since it is employed in scanning and 3D design to mean the assignment of color to geometric model surfaces. In more familiar usage, texture describes surface roughness. In industry and 3D scanning jargon, texture is actually color and not surface attributes that are assigned; the physical texture is already present in the 3D data as the spatial data that describes the object's surface.

"Texture mapping" describes the process where an image of a surface is overlaid or "mapped" to the object geometry during post-processing. Texture mapping is analogous to wrapping a thin film or skin over the data. This technique normally requires the use of a second camera (film or digital) to record a series of color images of an object's entire surface from different angles. These photographic images are later applied to the object's 3D digital data using special registration software during post-processing. Naturally, the mapping of a mosaic of images onto 3D spatial data, and then fitting the overlapping areas, is an art. Color capture must be further investigated, and in this, the conservator can play a vital role. Acting as a bridge between the color scientist and scanner designers, conservators can participate in specification and design of a new generation of scanners.

7.3 THIRD-PARTY SOFTWARE

Third-party software is any software used to work with the 3D data that is not part of the scanner system software. There are many 3D software packages available and most scanner manufacturers will recommend a package that complements their own system software. Usually this will be a software package that performs one or more data processing functions more efficiently than the scanner's proprietary system software. It is also not unusual for a scanner manufacturer to use third-party software for all of their post-processing work, from taking raw data to producing a final 3D graphic model. Generally, third-party software packages are designed exclusively to manage 3D data (at any stage from raw to final format), while a scanner manufacturer's priority is to design proprietary software that will run the scanner. This ensures the most accurate and high-resolution data capture and results in excellent raw data. Although not typical, there is scanner system software that will do everything well, from collecting raw data, processing, carrying out measurement functions, and final viewing of the finished 3D model. Since purchasing third-party software can be expensive, it is advisable to commit time and energy to researching the appropriate package for the needs of the organization. The benefits of researching system and third-party software cannot be overemphasized, as the software significantly impacts the research and viewing quality, and potential, of the 3D data. Two of the most often used software packages are Rapiform (INUS Technology, Inc., 601-20 Yeoksam-dong Gangnam-gu Seoul 135-080, Korea) and Polyworks (InnovMetric Software Inc., 2014 Cyrille-Duquet, Suite 310, Québec, QC Canada).

7.4 FREEWARE AND SHAREWARE FOR 3D VIEWING

There are alternatives to purchasing expensive third-party software. Many 3D graphic software companies offer low cost or free downloads (such as Polyworks) of their viewing software directly from their Web sites. Most of these viewers will be able to open a variety of common 3D file formats and allow a limited number of measurement and viewing functions. These free or low cost downloads make it possible to import, manipulate, and interact with the 3D graphic model. This would not be possible if the data were loaded onto the Web as a digital video, which is one common method used to view 3D scan data.

8. CONCLUSION

Although new to many in the heritage fields, 3D scanning is a mature and constantly improving technology. The evidence is found in the multitude of routine industrial and research applications in which scanning is used today. Even though few instances of systematic heritage scanning programs can be found, especially in North America, it is easy to imagine that 3D scanning will become a regular part of documentation and research for heritage organizations internationally.

Digitization of collections is mandated in many cases, and in the future 3D scanning will surely play an important role. Current digitization work most often refers to photography of one or more views of collection objects. The incorporation of 3D scanning and viewing introduces a new and significant degree of object interaction that makes this integration an invaluable and incomparable addition to the documentation repertoire. 3D data is being used to create virtual exhibition designs, both for individual display cases and whole exhibits. By preparing output for the Internet, a global audience can be reached. Such uses will help to reduce the handling of the objects in the future.

The development of 3D scanners is continuing, and instruments for heritage applications are benefiting from this development. The complexity and expense—as well as the rapid pace of change—may seem to justify a wait-and-see attitude for heritage work. However, the opportunity to influence the use and development of this remarkable technology is at hand. Not every organization needs a 3D scanner. It may be sufficient for the heritage professional to more fully understand the technology, and become better able to specify scanning needs while engaging contract professionals. In addition, familiarity with the technologies currently in use and under development will make successful application of 3D scanning possible when the opportunities inevitably arise.

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MELVIN J. WACHOWIAK is senior conservator at the Museum Conservation Institute, Smithsonian Institution. He graduated with a Master's degree from the Winterthur/University of Delaware Program in Art Conservation in 1989. He has been a conservator at the Smithsonian Institution since 1989, specializing in wooden objects conservation, and is program manager in charge of development and uses of 3D scanning. Address: Museum Conservation Institute, Smithsonian Institution, 4210 Silver Hill Road, Suitland, MD, 20746; wachowiakm@si.edu

BASILIKI VICKY KARAS is a contract objects conservator and 3D scanning specialist at the Museum Conservation Institute, Smithsonian Institution. She holds a BA (Anthropology and Classical Studies), an MA (Classical Archaeology), and a Master's degree in Art Conservation (MAC). Vicky has worked as an archaeologist and conservator on projects in Jordan, Canada, Italy, Greece, Guatemala, Mongolia, Honduras, and Mexico. Her primary research interests since 2004 involve the application of 3D scanning techniques in the noncontact documentation and preservation of cultural heritage. Address: as for Wachowiak; karasb@si.edu