Three-Dimensional Alternatives to Lithic Illustration

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Numerous publications have focused on illustration in archaeology and are still widely used and consulted by both professionals and students. These works range from books discussing drawing in archaeology more broadly (Adkins and Adkins 1989; Dillon 1985) to reference materials specifically geared toward illustrators or archaeologists working with lithics (Addington 1986; Chase 1985; Dauvois 1976; Martingell and Saville 1988). Additional drafting sources from external fields are also frequently consulted (Guptill 1976; Zweifel 1961).

While there are now other viable options available, lithic illustration remains the most common way of displaying stone artifacts in publications. Convention dictates that projects either must employ a lithic illustrator or archaeologists must draw artifacts—themselves—illustrations provide a visual record of a representative sample of an assemblage for external archaeologists to evaluate.

Since it is widely accepted that a photograph of a stone tool cannot actively substitute for a drawing, it has only been in recent years that a move away from lithic illustration has become possible. If the same information that interests archaeologists can be gained from a three-dimensional (3D) model as from a drawing, the objective and replicable mode of depiction should be considered as an alternative. Current technological developments facilitate and warrant this shift. Importantly, CT-scanners, surface scanners, and the application of photogrammetry have

ABSTRACT

Although alternatives have become available, pen and ink drawings of stone tools dominate archaeological publications. Despite the existence of a conventional illustration framework, the work produced by illustrators can be inconsistent and hinges on skill level and time commitment. Discussions going back to the 1880s critically question the use of illustrations for the purpose of scientific publication. Alternatives, such as laser scanning and photogrammetric modeling, are now available for displaying lithics. These alternatives can remove the subjectivity involved in artistic rendering, creating replicable results, regardless of who is collecting the data. In addition to creating more regularized and objective representations, there are a significant number of analytical and other benefits to adopting novel imaging techniques to depict stone tools in publications. A set of three-dimensional (3D) models are presented here to demonstrate the capabilities of laser scanning and, potentially, photogrammetric modeling as replacements for lithic illustration.

A pesar de que existen alternativas más objetivas, los dibujos en papel y tinta de objetos líticos predominan en publicaciones académicas. Aunque existen convenciones de ilustración, el trabajo de los ilustradores puede ser variable y depende de la habilidad y el tiempo empleado. Los problemas acerca la ilustración científica no son nuevos, ya que discusiones desde 1880 cuestionan críticamente la objetividad de las ilustraciones para publicaciones científicas. Algunas alternativas como el escáner láser y la fotogrametría están ahora ampliamente disponibles para las ilustraciones de lítica. Estas alternativas eliminan la subjetividad que implica un diseño artístico, generando resultados que son replicables más allá de quien haya producido los datos. Además de crear representaciones más objetivas, hay un número amplio de ventajas analíticas al adoptar nuevas técnicas de ilustración de lítica. Los investigadores pueden potencialmente realizar nuevos análisis digitales en 3D, ahorrar en su investigación, además de facilitar el acceso a colecciones excavadas globalmente. El artículo presenta una serie de modelos 3D que demuestran la potencialidad del escaneado láser y de la fotogrametría como reemplazos del dibujo lítico. Los modelos de escaneado láser son un sustituto ideal para las ilustraciones, mientras que los modelos fotogramétricos son en muchos casos inadecuados, pero presentan otras ventajas que han de ser tenidas en cuenta.

Advances in Archaeological Practice 2(4), 2014, pp. 285–297
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DOI: 10.7183/2326-3768.2.4.285

https://doi.org/10.7183/2326-3768.2.4.285 Published online by Cambridge University Press

become far more widespread in archaeology due to the increasing ubiquity of equipment and lowering costs of operation.

The application of 3D modeling methods in lithic studies has thus far been geared towards novel analytical techniques, or verifying techniques which were previously done by hand (e.g., Clarkson 2013; Richardson et al. 2011). For example, Lin et al. (2010) have used a Konica Minolta Sensing Vivid 910 scanner to substantiate lower-technology methodologies of surface area measurement, as employed by Douglas (2010) in the field to calculate cortex and core surface area.[1] Clarkson and Hiscock (2011) have refined platform measurements using 3D scans and also affirmed the accuracy of the methodology. Additional researchers have begun to work with geometric morphometrics, extracting landmarks from scanned models (Selden et al. 2014; Sholts et al. 2012; Shott and Trail 2010). Others have focused on the curatorial benefits of scanned models and the potential use in long-distance collaboration provided by a 3D database (Abel et al. 2011). Finally, some researchers have used scanners coupled with algorithms to accurately extract dimensional attributes of artifacts (Grosman et al. 2008).

Collection accessibility, preservation, and the creation of digital exhibits are additional benefits of digitizing artifacts (Ahmed et al. 2014; Bruno et al. 2010; Shott 2014). Entire journals have emerged to fill this growing niche, covering topics such as cultural heritage and the digitization of artifacts of all sizes (for example, the journal *Digital Applications in Archaeology and Cultural Heritage*). While still in its relative infancy, the dissemination of digital models en masse is promising. The benefits of being able to study collections remotely are significant and will provide a high level of collection accessibility once appropriately refined.

With the increasing availability of low-cost 3D modeling methodologies, it has become possible to accurately render artifacts through digitization. NextEngine Desktop 3D Scanners cost approximately $3,000 and have numerous analytical and preservation applications (e.g., Betts et al. 2011; Shott and Trail 2012).[2] Similarly, photogrammetric modeling is becoming more widespread in excavation contexts (De Reu et al. 2013). The equipment for this type of modeling is even more affordable than laser scanners, a complete set-up with software costing well under $1,000. Comparisons between laser scanning and photogrammetry are rare, but have been undertaken by some researchers (Koutsoudis et al. 2013). Unlike their drawn counterparts, which are useful for illustrating one concept, a digitized three-dimensional artifact, which can be sent to and manipulated on researchers' computers, retains further utility and analytical value.

A COMPARISON TO OTHER DISCIPLINES

While the application of scientific illustration in other fields obviously differs from that in archaeology, a general technological progression can be traced. A trajectory can be followed between time periods, with a shift toward depiction of individual specimens in an objective manner (Datson and Galison 1992; Topper 1996).

From the 1600s to the mid-1800s, "scientific" illustrators were known for displaying archetypes, which were composites representing the idealized specimen. This drastically changed in the late 1800s, when averages were discarded for realistic portrayals of individual examples. The composite representation left too much room for bias, or for unscientific representation. This shift to individual representation predated the advent of novel technologies, specifically the application of X-rays and photography as means of documentation (Datson and Galison 1992; Lopes 2009; Topper 1996).

Scientists put replicable methods of portraying individual specimens into practice as soon as they became available. Mechanical portrayals were much more synonymous with objectivity than artists' renderings even in the late 1800s, largely due to the level of the artists' interpretations (Datson and Galison 1992). While a photograph or X-ray certainly requires a degree of extrapolation, removing the illustrator removes one extra layer of interpretation. Additionally, to look at an illustration and understand it, an individual must be familiar with the abstract stylizations of illustration (Lopes 2009).

Those who study scientific images argue that there is still room for scientific illustration of composites, but not in the representation of particular specimens. In most scientific fields, the portrayal of individuals is most frequently done with machine-made images, and scholars agree that this is most appropriate (Lopes 2009). Given this rationale, it is worth taking into consideration potential replacements for illustration.

ISSUES WITH LITHIC ILLUSTRATION

While archaeologists frequently draw stone artifacts themselves, hiring artists who do not specialize in stone tool technology is also a common practice (Adkins and Adkins 1989; Chase 1985). Despite the fact that conventions and standards have been proposed, the quality of these illustrations remains highly variable. There are many stories of incorrect portrayals, depictions, and orientations of artifacts by illustrators. These issues may cause delays in publication, or errors in the publications themselves. Poor illustrations can be damaging to readers' interpretations of archaeological material (Dillon 1985). Though these criticisms are valid, lithic illustrations, when crafted correctly, can accurately depict and stress specific stylized attributes-—the interpretation of an experienced lithic illustrator can clearly and concisely sum up an artifact in an aesthetically pleasing way. For this reason, it is desirable for illustrators to be well acquainted with stone tools, or to work in close consultation with an archaeologist (Addington 1986; Chase 1985; Dauvois 1976).

Photographs are considered poor at depicting lithics because of their lack of selectivity. Lithic illustrators select attributes of a stone tool that they determine to be intentional, excluding unintentional or geological characteristics outside of the stylized catalog (Lopes 2009). Illustrators have the opportunity to stress different aspects of an object, calling attention to characteristics as they see fit. According to Adkins and Adkins (1989), archaeological illustrators choose to portray the relevant details, leaving out superfluous ones. Decisions regarding relevant details often come down to time or funding constraints, thus leading to

https://doi.org/10.7183/2326-3768.2.4.285 Published online by Cambridge University Press

images in various stages of completion in some respects (also see Addington 1986). Illustrations vary based on the skill set of the illustrator and the time invested in any particular drawing.

Conventions developed by lithic analysts emphasize specific protocols that lithic illustrators are recommended to follow, such as indicating the directionality of flake scars and observing certain rules on shading and the position of lighting, among others. Any number of illustrators, given the same object, will return different stylized images. Archaeological illustrations also vary depending on the intent-—where the drawing will be used and for what purpose (Adkins and Adkins 1989). The issue of standardization is pronounced, to the point that it has been noted by both lithic analysts and illustrators themselves (Addington 1986; Chase 1985).

Lithic illustration has its base in stylization, which is a standardized departure from what is actually being observed. An expert who knows how to read the drawings of lithic illustrators is familiar with the language and conventions that are supposed to be common across depictions. Ripples are perhaps the most common marks employed by illustrators and are the most stylized. They are used to indicate the directionality of the force, and are often portrayed on paper as more visible than in reality. Depending on the overlap of the ripple marks, the order of flake removal can be determined. Ripple line thickness can indicate the approximate amount of force used to detach a flake, although this has not been meaningfully quantified by archaeologists. Stylization is also readily apparent with cortex, in addition to numerous other stone tool attributes. In the case of cortex, a regularized stippling is used, which often bears no resemblance to the piece but has a known meaning (Addington 1986).

Finally, archaeological illustration is costly in terms of time and money. The quality of images is often controlled by a project budget that dictates the resolution at which objects can be illustrated. Regarding time, archaeologists who draw artifacts compromise their ability to conduct other analyses or work.

LIMITATIONS OF CONVENTIONAL PHOTOGRAPHY

According to guides on archaeological illustration, photographs may be disadvantageous because of their level of realism. A realistic photograph does not stress the same traits emphasized by an illustration, frequently evident only under different lighting (Adkins and Adkins 1989). Often the characteristics that archaeologists and illustrators deem important cannot be seen well in photos and may be choked out by color and other details an illustrator can selectively omit.

Archaeologists writing on the photography of stone tools have recognized that the method introduces some problems, specifically in terms of color and reflection. In order to overcome these issues, they have explored methodologies of manipulating light sources in a controlled manner. Some archaeologists recommend using light filters on cameras to mitigate glare, specifically with obsidian (Rovner 1974). Others suggest covering artifacts in a type of paint, or other surface treatment, to eliminate the reflection of the raw material (Callahan 1987; Prokop 1985). This method has not caught on with archaeologists, although some experimental archaeologists have used this methodology with non-archaeological specimens (Dibble and Rezek 2009; Rezek et al. 2011).

In the past, some archaeologists who supported the use of photography focused on its practicality over illustration. When artifacts could not be transported out of the country of origin, photographs could be taken. The collected photographs were then intended for later use as the basis for illustrations. Scarcity of time or expertise was the major reason for choosing photography over illustration (Prokop 1985).

More recently, the use of photography in publications has become commonplace, perhaps as a result of improving digital technology. Photographs are used in a variety of ways, including to display raw material variability or to indicate flake removals with directional arrows (Manuel et al. 2013; Scerri 2013). In another example, Stout et al. (2014) use photographs to effectively depict hand axes from different skill levels of flintknappers, as well as for close-ups to show platform preparation. However, when books are being reviewed, mixed feedback is given about using only photographs in publication. Holdaway and Stern (2004) used photographs extensively in their book on Australian stone tools. One reviewer of this work noted that the photographs worked well in place of drawings, while another expressed that traditional illustration would have strengthened the publication (Moore 2005; Odell 2005). Although the use of photographs is widespread and appropriate in a majority of contexts, it would be difficult, at best, to consistently extract the same level of information from a photograph as from a stylized lithic illustration.

METHODOLOGY

Specimen Selection

Several lithic artifacts of experimental and archaeological origin were selected to be modeled. Commonly illustrated objects, as well as flakes exhibiting frequently stylized attributes, were chosen. Models were generated using both a NextEngine Desktop 3D Scanner and a Canon DSLR in conjunction with AgiSoft PhotoScan Pro photogrammetric software.[3] Commonly stylized illustration features were singled out to verify whether the 3D models could serve as adequate replacements for illustration.

The modeled objects were mainly selected from Middle Paleolithic contexts to demonstrate a range of flake removals and retouched areas suitable as proxies for flaked stone tools in general. Multiple Mousterian type scrapers and denticulates were selected for scanning to ascertain the ability of 3D models to indicate retouch intensity. Two cores and one typical Acheulean handaxe were selected in order to demonstrate the ability of 3D scanners and photogrammetry to detect ripple marks from flake removals in complex patterns. The artifacts were of various materials, some explicitly chosen because they were fashioned from coarser material, or fine flint, and others were cortical.

Computer and Camera Hardware

The computer used for the processing portion of this study was an ASUS S400CA, with 4GB of RAM, and an Intel Core i3-3217U CPU. The camera employed during the photogrammetry com-

https://doi.org/10.7183/2326-3768.2.4.285 Published online by Cambridge University Press

ponent of the project was a Canon EOS Rebel XSi 12.2 megapixel DSLR, with a standard kit 18-55 mm IS lens. While more powerful computers and cameras are often used in archaeological applications, these selected devices are representative of commonly available and employed machines in the range of most project budgets.

Data Collection Laser Scanning

For the purposes of comparison, a NextEngine Desktop 3D scanner was utilized. This unit is made up of a scanning station and rotational platform where the object is placed during the data collection. NextEngines capture 3D information using a laser system, as well as photographs, which are subsequently layered on the 3D model. For this project, the 3D mesh without the photographic overlay was desired.

Artifacts were placed on the 3D rotational turntable and put into focus in the ScanStudio HD Software. Depending on the size of the object, the artifact was placed at a specific distance from the scanning unit on the turntable. All specimens were scanned in high definition, which maximized the amount of points collected on each object.

After initiating the scanning process, a laser beam sweeps across the object and records many thousands of individual points. Subsequently, these points are connected into a triangular mesh, which makes up the texture of the object. A scan set was taken approximately every 40 degrees throughout a complete 360 degree rotation. This process took approximately 30 minutes in high definition. After the initial scan was taken, a second 360 degree scan was performed after flipping the artifact on a different axis. This creates two separate scan groups, which need to be merged into one object during processing. Using smaller "bracket" or "single" scans is also possible and commonly practiced to reduce data collection time, but this protocol was not followed here.

Laser-Scanning Processing and Visualization

The data collection phase generates groups of scans, which need to be merged into one coherent model. The first step is to edit out unnecessary elements of the scan, including pieces of the stand used to hold the object (Figure 1). This initial step takes less than 10 minutes per object.

After unnecessary elements are removed from each of the scan groups, the groups are stitched together into one cohesive scan. This involves locating at least three different points on each of the scan groups that are the same. Using these points, the software aligns the two models together. In order to have the model ready for analytical purposes, fusing the scan families into one group is necessary. This eliminates any overlapping areas in the model and creates one cohesive object. For the purposes of this project, the merging step averaged approximately 30 minutes per object.

While ScanStudio software is useful for merging scans, for further use or analysis it is advantageous to export them to software that performs more tasks. Aside from this merging function, ScanStudio only determines the volume of the model.

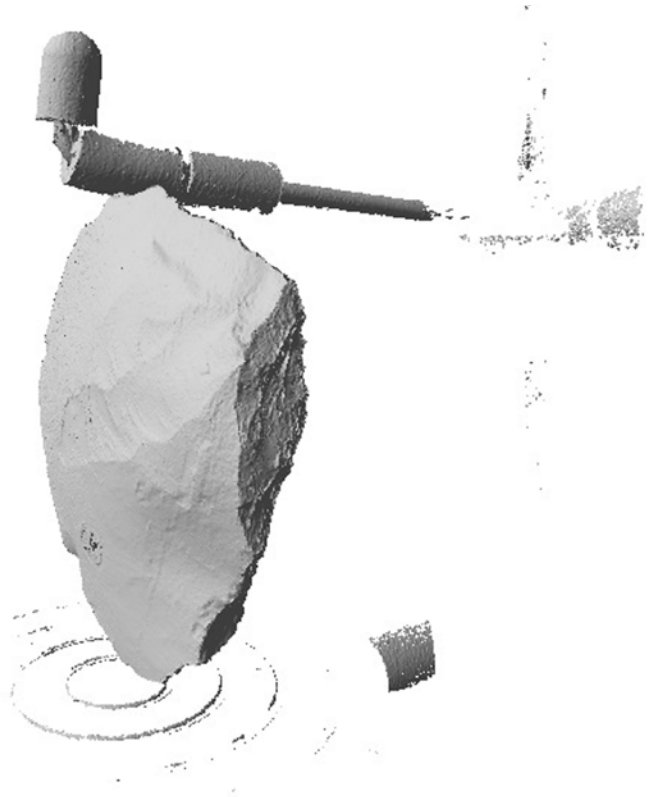


FIGURE 1. Scan prior to processing as displayed in ScanStudio Software (Nextengine Inc.).

ScanStudio licenses are only available with the purchase of a NextEngine Scanner, without which it cannot be used to manipulate models. The ScanStudio file output is unique to the software; it is therefore necessary to save work in another common file format to manipulate models using other programs.

In ScanStudio, 3D models were converted to .ply format before being exported into MeshLab, a free program with significant analytical and processing capabilities.[4] Most importantly, it is here that the direction of light can be manipulated, allowing users to see optimal detail on their object, depending on how the light is held. Models can be easily rotated and exported to be included in reports or publication.

After processing, the individual scans were placed in positions to emphasize commonly stylized attributes. The levels of retouch and other characteristics are highlighted below, demonstrating that the same level of information can be drawn from a scanned representation of a lithic artifact. The total time investment per scanned object using a NextEngine averaged 1 hour and 40 minutes.

PHOTOGRAMMETRY DATA COLLECTION

Photogrammetry is frequently practiced for both smaller artifacts and larger archaeological or landscape features. At its most basic,

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photogrammetry entails the use of almost any digital camera and laptop computer, as well as relatively inexpensive software. Photographs are taken from various angles. Depending on the software used, as with laser scanners, points that are shared in common between the photographs are lined up, and a 3D model is generated. The overlay of photographs allows a field of depth to be generated, on which measurements can be taken.

As noted by previous work, 3D models generated with photogrammetry have the potential to be more variable in quality (Sumner and Riddle 2008). Though exceeding the scope of this paper, it is recommended that a consistent and repeatable methodology be created in the future as a suggested protocol for researchers, based on different common geometries of stone tools.

Using a Canon EOS Rebel XSi 12.2 megapixel DSLR equipped with an 18-55mm IS lens, an artifact was placed on a black matte background to help with subsequent processing. Photographs were taken at a variety of angles, as the photographer moved around the stationary object. Approximately 10-15 photographs were collected for each artifact placement, totaling approximately 30 photographs per object. Photos were taken at even intervals around the object at least every 30 degrees, at two different horizon angles. Generally, a single artifact could be completely photographed in less than 10 minutes.

Lighting was closely controlled using two overhead fluorescent lamps, which minimized the quantity of shadows and regularized the amount of light across the surface of the lithics. Objects were typically placed in two different positions. Flakes or tools made on flakes were placed on dorsal and ventral surfaces; bifaces were rotated on their two respective faces; and cores were rotated, based on their individual geometries. In one instance, when the raw material surface was highly reflective, a glass powder coating was applied to the material to reduce the irregular reflection of light.

Photogrammetry Data Processing and Visualization

Following data collection, photos were imported into the program AgiSoft PhotoScan Pro. AgiSoft can be used for both constructions of larger landscape features and the modeling of individual artifacts. Fortunately, the software is relatively inexpensive and simple to navigate, making processing of scans easy.

To process a model, first a group of related photographs is imported into the program. These photographs can be aligned immediately or, preferably, the artifact will be outlined, or "masked," which speeds up model processing and eliminates the inclusion of unnecessary background noise in the initial digitization. From here, a high-density point cloud of the object is generated. Using this high-density cloud, a 3D mesh is created, which represents the finished product of one orientation of the artifact. The initial model generated has a photographic overlay, which can be removed to see a gray or blue-scale textural model.

The way an artifact is processed in AgiSoft has significant implications for how the final product is visualized, but it is significantly constrained by computer hardware. These same processing protocols can also impact the amount of time spent per model. To process one side of an artifact with a "medium" quality output, 30 minutes may be required. The same artifact generated with "high" quality output can take several hours. To minimize time constraints, the midrange settings for creating point clouds were selected. Note that the minimum recommended computer specifications for operating the software are very high—it is unlikely under normal circumstances that personal or project computers at this time will meet AgiSoft's recommendations of at least 32 GB of RAM, or processor speed. However, using a computer with higher specifications would decrease the processing time per model significantly and increase model quality.

RESULTS

Overall, commonly stylized characteristics of lithics typically illustrated in publications are discernible in the scan images. Below, each of these characteristics is outlined with a close-up on the 3D example (both laser-scanned and photogrammetric) and photograph, demonstrating their presence. Individual specimens were chosen as representative of commonly stylized features. Photogrammetric and laser-scanned models can also be displayed with a textured photographic overlay. Although useful for display purposes, this overlay was excluded from the present study, given that stylized attributes of drawings were of main concern.

Flake Scar Directionality

Ripple marks, indicating the directionality of force, are present in 3D scans. As when holding an artifact, they are best visualized in software where the direction of the light can be manipulated (Meshlab was used here). Ripple marks are easily discernible on both the ventral and dorsal surfaces of flakes, as well as in more complex patterns, on handaxes and cores. Order of flake removal can be ascertained in some cases where ripple marks are overlapping (Figure 2a).

By contrast, directionality can only sometimes be inferred from photogrammetric models. Only the clearest ripple marks are visible on these models, which calls into question their ability to directly replace lithic illustration (Figure 2b).

Retouch Intensity

Retouch intensity is readily apparent in the scanned models (Figure 3a). As with lithic illustration, indicating whether or not the observed retouch is anthropogenic or taphonomic in nature is important.

On photogrammetric models, retouch intensity is visible to various degrees. Heavy retouching of an artifact can clearly be seen. Lighter instances of retouch, which could also be evidence of abrasion or artifact use, are less easily discerned. As discussed below, problems in displaying raw material coarseness obstructed the clarity of retouch in the displayed sample (Figure 3b).

Presence of Cortex

The presence of cortex, traditionally depicted through irregular stippling, is also distinguishable using laser scanning (Figure 4a).

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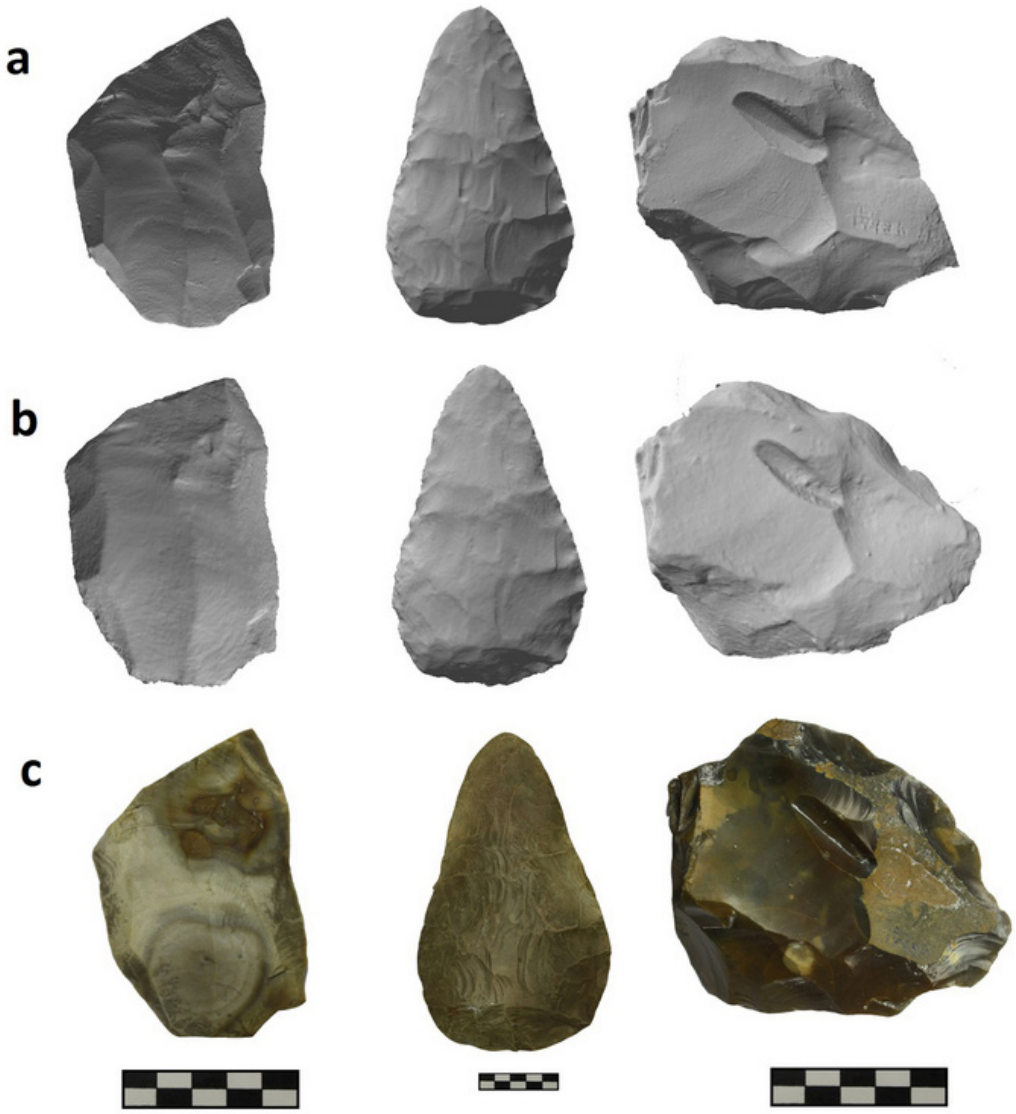


FIGURE 2. Images demonstrating ripple directionality. From left to right: Levallois flake; handaxe; discoidal core. Top row (a) demonstrates laser scans; middle row (b) shows photogrammetric models; bottom row (c) shows photographs.

Although it has been well established that 3D scans can be used to calculate cortex measurements (Lin et al. 2010), its visibility is reemphasized here.

Cortex is easily discernible in the photogrammetric models. However, in comparison to laser-scanned models, the boundaries are not as clear. Clear boundaries can be discerned on the cortical flake being illustrated, where a distinct line between cryptocrystalline chert and the chalky cortex is present. This was not the case when the cortex graded more slowly into flint in the core modeled below (Figure 4b).

Raw Material Coarseness

Material coarseness is clearly visible in laser-scanned models. Individual impurities can be seen in materials, including, in some cases, likely forms of microfossils. While finer-grained flints appear smooth in laser scans, with a higher degree of rippling visible, coarser material shows up pockmarked and rough (Figure 5a). By contrast, it is more difficult to distinguish material coarseness based on photogrammetric models. While, in general, one can distinguish between coarse and finer material, the models made in AgiSoft did not have the same level of resolution as laser scans. Often, the surface does not look true to the individual artifact in the photogrammetric models. The surface of fine flint at times looks rougher than in reality, while coarser flint takes on a smoother appearance (Figure 5b).

BENEFITS OF 3D MODELING

General Benefits

In lithic studies, it is always desirable to keep inter-observer error to a minimum when conducting analyses, and this principle can be extended to lithic illustration. While a well-illustrated drawing

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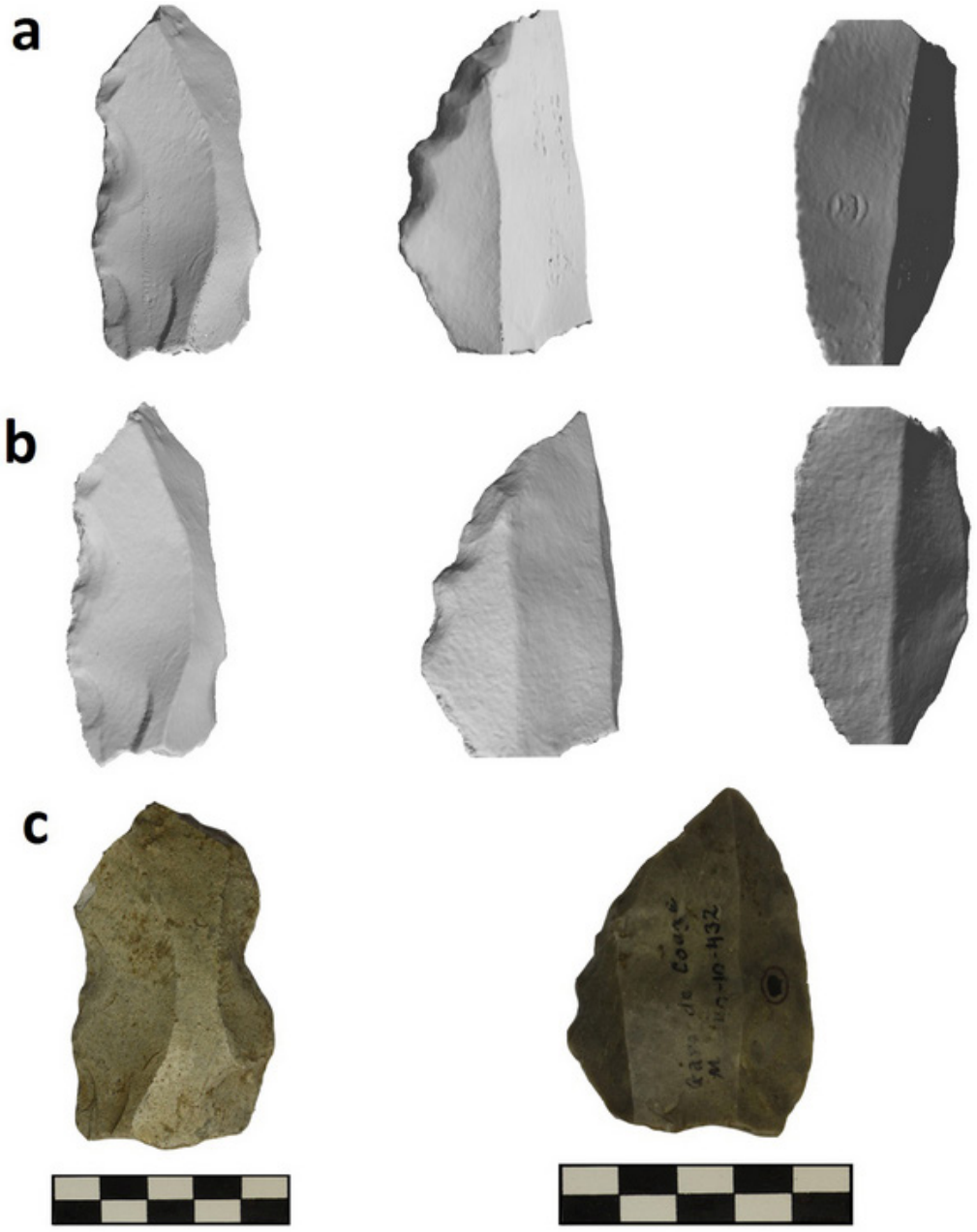


FIGURE 3. Retouch of varying intensity. From left to right: side scraper with heavy retouch; scraper and denticulate, shown in two positions. Top row (a) demonstrates laser scans; middle row (b) demonstrates photogrammetric models; bottom row (c) demonstrates photographs.

may have consistent takeaway messages, 3D models lack an external layer of interpretation. In the case of laser scans, several scans of the same artifact yield essentially identical models, as has been established using NextEngines in a biological anthropological context. Importantly, this standardization of results is consistent across observers (Sholts et al. 2010).

One of the justifications for the use of lithic illustrations relates to the ability of an illustrator to depict how the object is seen in different lightings (Adkins and Adkins 1989). This concern is becoming outdated with advances in technology. Publications can now commonly include 3D models embedded in text and PDFs. Light and angles can be manipulated, which allows the reader to illuminate any evidence of directionality of ripples or similar attributes.

Specifically, the increasing ubiquity and decreasing costs of 3D laser scanners, as well as photogrammetric processing software, offer a viable and objective alternative to reliance on illustrations. Many departments and researchers now have access to

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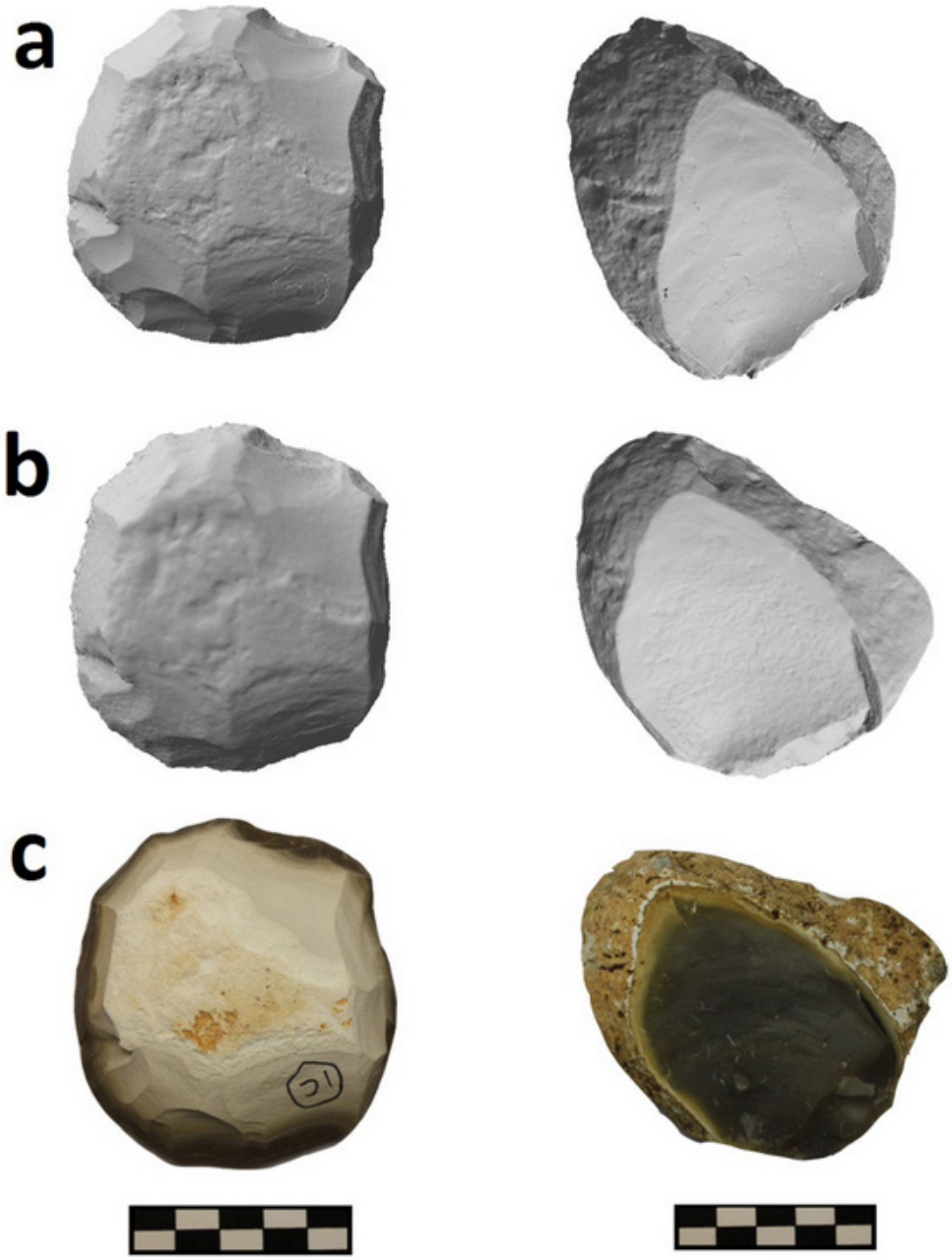


FIGURE 4. Visualization of cortex. Single-surface core on left, cortical flake on right. Top row (a) demonstrates laser scans; middle row (b) demonstrates photogrammetric models; bottom row (c) demonstrates photographs.

portable scanning units, which can eliminate or allow sharing of costs. Both NextEngines and DSLR cameras are easily transported into the field and can function anywhere with a power source and laptop, thus potentially reducing the substantial project cost and completion time that lithic illustration involves.

For the purposes of depicting lithics for publication, a minimal amount of processing needs to occur. If the image is for a traditional paper publication, scan groups do not even necessarily need to be stitched together. This has the potential to reduce the time investment per object even more significantly.

Lithic illustrators are artists-—in other words, they are generally highly skilled at what they do, and not anyone can illustrate. By contrast, it takes a short time to become familiar with the protocols of producing 3D models, and it is comparatively low-skill. So, while not everyone can illustrate, almost anyone can run a portable scanning unit. This could likely translate directly to project costs, which may potentially be lowered through employing scanners.

As has been demonstrated by previous studies, a 3D model can be used and manipulated in many ways that an illustration cannot. That is to say, an illustration is useful only for the publication

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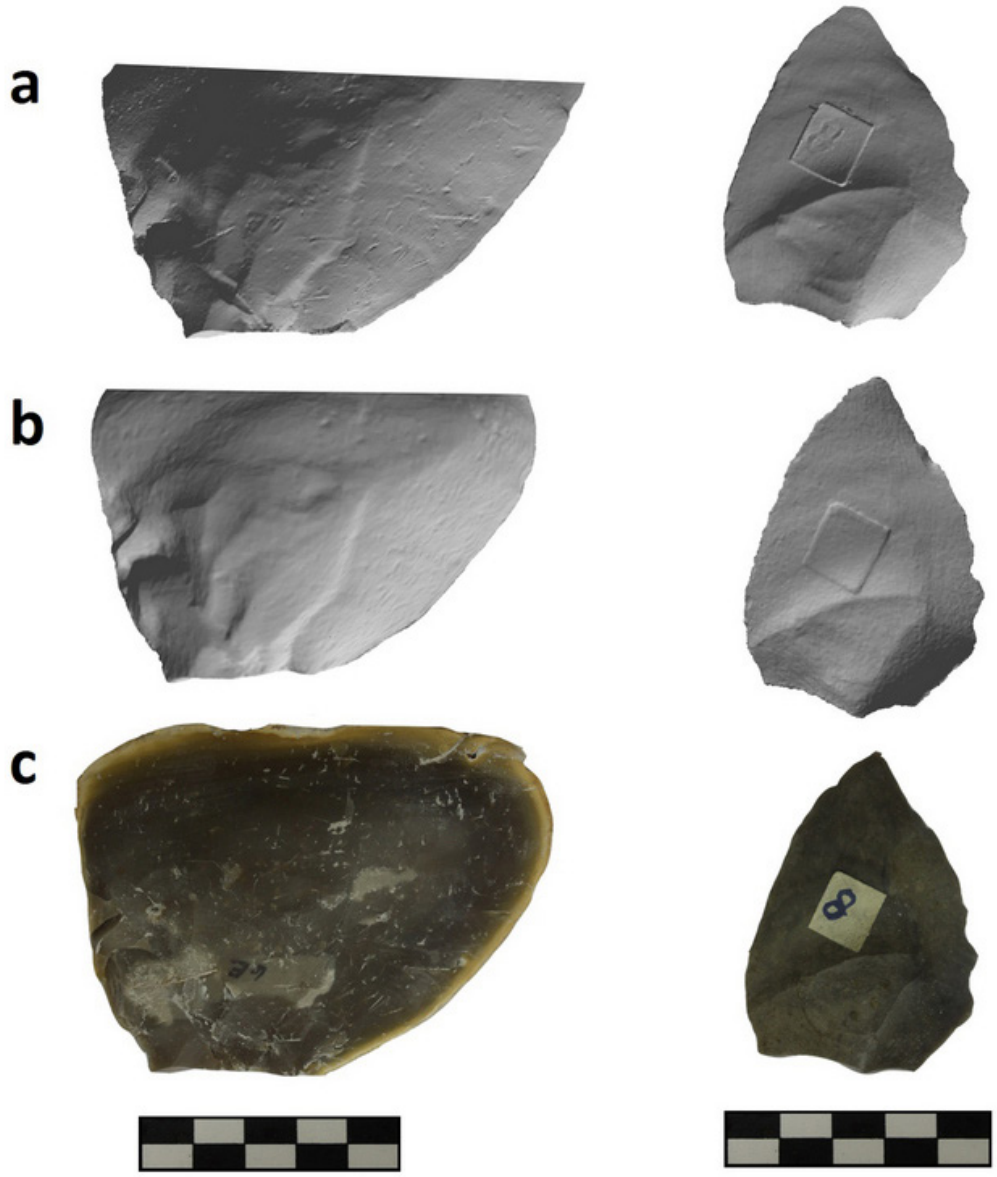


FIGURE 5. From left to right: cortical flake made on coarse flint; scraper and denticulate made on a finer-grained flint (artifact label present on this specimen). Top row (a) demonstrates laser scans; middle row (b) demonstrates photogrammetric models; bottom row (c) demonstrates photographs.

and portrayal of that object, serving no further archaeological benefits. In comparison, a scan can be used to depict a lithic in a publication and then be subsequently used for educational or analytical purposes.

Similarly, orientation errors common in illustration could be completely eliminated. If an illustration is incorrectly oriented or depicted, the illustrator may have to abandon much of his or her previous effort. The adoption of 3D models would eliminate this issue. An incorrect orientation or lighting angle can simply be fixed by rotating the object in a computer program, without requiring that the artifact be redrawn from another angle.

Advantages of Laser Scanning

Three-dimensional scans are superior to photogrammetric models in terms of accurately representing objects. While laser scanning is truer visually, it is unclear whether or not commonly undertaken analyses, such as observation of cortex ratios or measurements of platform area, would be significantly impacted. In the future, studying the analytical accuracy of both laser scanning and photogrammetry may shed some light on this.

Viewing the creation of lithic models as a time investment, the difference between active and passive time is worth noting. That

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is, the scanning protocol itself is not an active one; an archaeologist can set something to scan and return half an hour later to reorient an artifact. For analytical purposes, the stitching process is highly automated, although scanner operators are required to align scan groups with one another to generate a complete model.

If models are being processed at a later time for analyses, when access to the archaeological material is no longer available, laser scanning provides a distinct benefit. It seems easier to assess where "holes" (or areas where points are unavailable for various reasons) will be present in scanned models. In other words, it is possible to see potential issues in models before you stitch them together, when it may be impossible to rescan a portion of an object.

Advantages of Photogrammetric Modeling

Although laser-scanning speed will undoubtedly become more rapid in the future, currently a significant time investment is required for each object. While a NextEngine might take up to 60 minutes to collect all of the data needed to make a complete 3D model, enough photographs could be taken to make a photogrammetric model in 10 minutes.

Accessibility is the strongest advantage of photogrammetry. While not every project will have a NextEngine, most all certainly have a DSLR camera. Coupled with the low-cost software most frequently used by archaeologists, it is possible to create photogrammetric models inexpensively.

DISADVANTAGES OF 3D MODELING

General Disadvantages

While in many cases creating a 3D model is a viable alternative to conventional 2D illustration, portable scanners and photogrammetric modeling have drawbacks that must be taken into consideration. However, these problems will likely be resolved with future technological advances.

Issues of material type may be problematic when attempting to scan an assemblage. NextEngines are notorious for being unable to scan black or highly reflective material, and units are provided with a type of powder with which to coat the object to correct these issues. Similar issues were noted when capturing images for photogrammetric models. In one case, it was necessary to coat the object to cut back the surface reflection.

Additionally, while the cost of data storage continues to decrease exponentially, scan files can be large. Individual scan files for this project for the NextEngine ranged from 200-700 MB, depending on the size of the object and resolution of the scan. Photogrammetric file sizes ranged between 2 and 10 MB in size for this project, which are significantly smaller. While not prohibitive in small quantities, larger collections of scans take up a significant amount of space and would be impossible to disseminate via internet.

Disadvantages of Laser Scanning

One of the major issues of using portable laser-scanning units is the lower size limits of what can physically be scanned. While these lower limits have not yet been tested, retouch and some instances of fine abrasion would be unlikely to register clearly with the scanners. In the case of small retouched pieces, less portable, more expensive options would have to be utilized. Many higher-power alternatives are available, but these, like the micro-CT scanner, are neither portable nor frequently at the disposal of archaeologists.

The $3,000 price tag, which is still at the high end of cost for many projects, is potentially prohibitive for the adoption of laser scanners for field use. However, as laser scanners become more common, the likelihood of access will also increase. The cost of sending artifacts to be scanned would be substantially lower than having them illustrated, relatively speaking. (Even the cost of micro-CT scanning artifacts is low, calculated at less than $2 per artifact.)

Photogrammetry

As previously noted, the variation in 3D models generated in PhotoScan Pro was significant. A number of independent variables dictate the quality of models generated. Different lighting set-ups created significantly different results. Additionally, models differed depending on the settings used in the software while processing the material. Until a methodology is demonstrated that can decrease this type of user noise, the variability in these models cannot be ignored.

While the speed with which photographs can be collected to create photogrammetric models reduces time spent in the field collecting data, the advantage is certainly lost when processing time is included. For each model made with photographs, approximately one hour was required to process a model. Much of this time is spent allowing the computer to process the model, so the procedure does not require constant attention. This will likely be remedied with the use of better computer hardware, which in the near future will undoubtedly become more accessible.

OTHER IMAGING SOLUTIONS

While this paper has stressed portable laser-scanning units as the most viable option for replacing lithic illustrations, other authors have proposed feasible options for capturing 3D models of artifacts. Specifically, researchers have stressed the feasibility of using micro-CT scanners as a viable low-cost option for scanning lithic artifacts. Costs have been estimated by some studies at approximately $2 per flake, which is low in comparison to the costs of a lithic illustrator (Abel et al. 2011). White light scanners, such as the Breuckmann smart*SCAN*, have also been used to accurately model lithics (Bretzke and Conard 2012).[5] Although micro-CT scanners, white light scanners, or other options may provide a solution to representing lithics, practicality dictates that it is usually not possible to transport collections to a location where such resources are available.

https://doi.org/10.7183/2326-3768.2.4.285 Published online by Cambridge University Press

FUTURE APPLICATIONS OF 3D MODELING

In the future, it is easy to imagine significant data-sharing initiatives of 3D archaeological models via the internet. Recent work by Ahmed et al. (2014) demonstrates the feasibility of digitizing larger collections of artifacts in an "assembly line" fashion. While it might be a long time before large quantities of 3D models can be shared on the internet, due to limitations of storage space, photographs used to create models take up far less space and can be shared more readily. Although photogrammetric models do not currently represent an ideal replacement for lithic illustrations, this may change in the future as processing capabilities improve.

Under this suggested protocol, researchers may take a series of photographs of as many artifacts as required to create 3D models. Data acquisition for each of these artifacts could take a matter of minutes. Archaeologists may collect photographs for few objects, or for a larger number. These photographs can easily be stored online and processed at any time and in any place. Photographs form the raw data for photogrammetric 3D models. Once a 3D scan is processed, it becomes one entity and cannot be reverted back to its original photographic form. However, keeping the raw data available leaves potential for future model processing software to either more efficiently or more accurately extract data from the photographic samples (see Ahmed et al. 2014 for a full discussion of this issue). Three-dimensional models can then be stored in larger numbers, left unprocessed until they are needed for some analytical purpose. If a researcher requires a sample of cores to work with, he or she may simply select cores from the assemblage and process the previously existing photographs of an artifact that may be many thousands of miles away, or for some other reason inaccessible.

As archaeology becomes progressively more digitized, it can be expected that the utility of 3D models will increase significantly. Specifically, 3D printing has the potential to change how collections are studied. In years to come, instead of flying to a foreign country to study a collection, the objects may be printed in 3D or studied on a computer screen. Portions of a budget traditionally set aside for airfare and lodging may then be appropriated to printing or database costs, and collections from distant places may be studied at home institutions.

CONCLUSION

Novel technologies have long rendered scientific illustration out-of-date in many other fields, at least in the depiction of particulars. Despite the presence of available technology, their adoption has not been as widespread in archaeology, where objectivity in artifact depiction has not been of primary concern. However, the increasing ubiquity of low-cost portable scanning units provides impetus for change.

A comparison of photogrammetric models to laser-scanned models demonstrates that only laser-scanned models are currently appropriate as illustration replacements, although additional benefits of photogrammetric models can be suggested. Data for photogrammetric models can be collected quickly, and the equipment required for collection is inexpensive. With increasing computer processing capabilities, it is expected that the gap between the two modeling types may be decreased. Most importantly, models generated with a NextEngine can accurately render aspects of artifacts that are traditionally illustrated, using a methodology of data capture lacking intermediary interpretation. Cortex, ripple marks, and retouch intensity are all readily visible in 3D models generated through laser scanning.

In addition to the benefits of depicting stone tools consistently, a number of analytical advantages can be stressed. Adopting 3D scanning has the potential to reduce project costs in the long-term and can be performed by relatively unskilled crew members as a tangential assignment. The creation of 3D models for the purpose of displaying objects also opens up the possibility of using the models for various analyses. Perhaps most importantly, the widespread use of digitization will increase the accessibility of collections to researchers, as protocols are established for efficient storage and dissemination of model files. While there are some drawbacks to employing portable modeling technology, the benefits far outweigh the potential limitations.

Acknowledgments

I would like to thank Dr. Rolf Quam for providing access to the Binghamton University Virtual Anthropology Laboratory for this project, as well as Drs. Harold Dibble and Deborah Olszewski for reviewing the manuscript at various stages of its completion. This material is based upon work supported by the National Science Foundation Graduate Research Fellowship Program (Award no. DGE1144152). Any opinions, findings, conclusions, or recommendations expressed in this paper are those of the author and do not necessarily reflect the views of the National Science Foundation.

Data Availability Statement

The artifacts and experimental pieces represented in this study are housed in the Archaeology Laboratory at the University of Pennsylvania Museum of Archaeology and Anthropology, Fourth Floor, 3260 South Street, Philadelphia, PA. Three-dimensional models are stored in the same location. The original artifacts used in this study include catalog numbers 37-30-11, 40-10-432 and EH-17436. The experimental artifacts for this project come from the lab's teaching collection and include experimental pieces numbered E-1A, E-1B, E-1C, and E-4E. All inquiries regarding access to 3D models or artifacts can be made to Dr. Harold Dibble, Curator-in-Charge, European Archaeology Section, University of Pennsylvania Museum of Archaeology and Anthropology, via e-mail (hdibble@sas.upenn.edu) or phone (215-898-7073).

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NOTES

1. Konica Minolta Sensing Vivid 910 scanners are produced by Konica Minolta Sensing Americas, Inc.
2. NextEngine Desktop 3D Scanners and accompanying software, ScanStudio HD, are produced by NextEngine, Inc.
3. AgiSoft PhotoScan Pro was developed by AgiSoft LLC.
4. MeshLab was developed by the Visual Computing Lab ISTI-CNR.
5. Breuckmann smart*SCAN* white light scanners are produced by AICON and Breuckmann.

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https://doi.org/10.7183/2326-3768.2.4.285 Published online by Cambridge University Press