DIGITAL HERITAGE AND ARCHAEOLOGY IN PRACTICE

Presentation, Teaching, and Engagement

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Empowering Undergrads in 3D Digital Imaging

Lessons from the DIVA Lab (Digital Imaging and Visualization in Archaeology), Louisiana State University

Heather McKillop

The transition to digital approaches in archaeology includes moving from 2D to 3D images of artifacts. This chapter includes a discussion of creating 3D images of artifacts in research with students, formally through a course, and informally in a 3D lab and during field research. Students participate in an ongoing research project by 3D digital imaging objects and contextualizing them. The benefits of 3D images of artifacts are discussed for research, instruction, and public outreach (including making 3D printed replicas for teaching and exhibits). In the 3D digital imaging course, students use surface laser scanners to image small objects that would be encountered in an archaeological excavation, and are presented with objects of increasing difficulty to image over the course of the semester. Midway through the course, each student is assigned an artifact for a project to include 3D laser scanning and photogrammetry, digital measuring, and research. Students write weekly blog updates on web pages they each create. Students learn to measure digital images and manipulate them with other software. The use of open-source software is encouraged when available. Options for viewing 3D images are discussed so students can link 3D scans to their web pages. Students prepare scans for 3D printing in the Digital Imaging and Visualization (DIVA) Lab. This chapter includes a discussion of research and instruction in the DIVA Lab, the Maya field project that created the need for the DIVA Lab, and the use of 3D technology in research and heritage studies in the Maya area.

3D Digital Imaging in Field Research

The impetus for the 3D digital imaging course developed from the need to obtain research-quality, 3D digital images of salt-waterlogged wooden, ceramic, and other objects from field research at underwater Maya sites at the Paynes Creek Salt Works in Belize (McKillop 2005, 2016, 2019a). Wooden posts and other architectural remains dating to the Classic period (AD 300–900) are preserved in red mangrove (*Rhizophora mangle*) peat that forms the sea floor and extends to depths of over four meters. The mangrove peat provides an anaerobic environment in which biotic decay is minimal. Since wood normally decays in the tropical landscape of the Maya area, the wooden buildings at the Paynes Creek Salt Works are the material record of the pole-and-thatch architecture that likely dominated ancient Maya communities (Haviland 1985). The 3D scans need to be both a research record of the material and a source for research. Not only are the objects property of a foreign government, but they are saturated with salt water and fragile, which presents challenges to their study. The artifacts associated with the wooden structures are mainly briquetage—the pottery vessels from boiling brine over fires. If allowed to dry, the salt moves to the surface of pottery vessels and expands, which cracks and defoliates the surfaces. When the waterlogged wooden posts and other wooden objects dry, the wood shrinks and decays (McKillop 2019b).

Total station mapping of 4,042 wooden posts and other architectural wood at 70 underwater sites at the salt works revealed the rectangular outlines of pole-and-thatch structures (McKillop 2019a). Digital data were transferred from the total station to a GIS, with some map data (UTM coordinates and

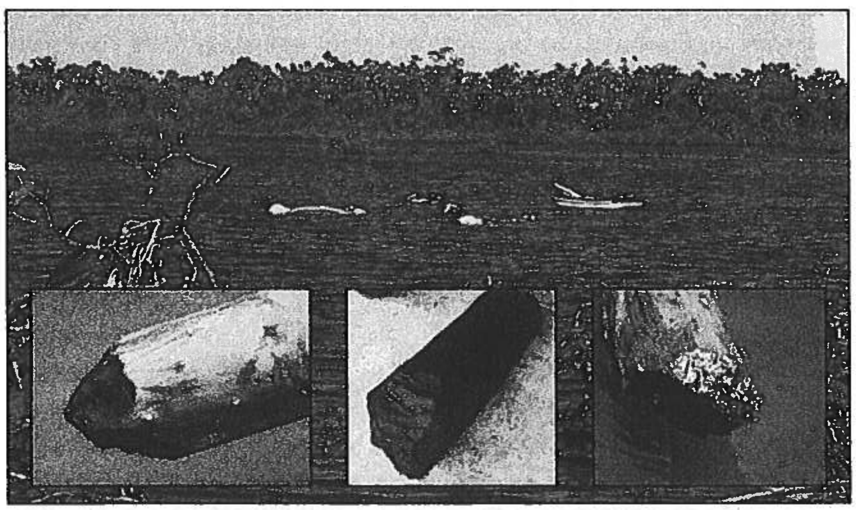

Figure 13.1. Wooden building posts preserved in red mangrove (Rhizophora mangle) below the sea floor, Paynes Creek Salt Works, Belize, with snorkeling archaeologists in background.

other post data on a Microsoft Excel spreadsheet) later uploaded to open-source QGIS software (McKillop 2016). Many of the structures were salt kitchens where brine was boiled in pots over fires to make salt, a basic biological necessity that was in limited supply in large lowland cities, including nearby inland sites in southern Belize (McKillop 2005, 2019a; McKillop and Sills 2016, 2017). A sample of posts was excavated to study their sharpened distal ends, along with several thousand samples from posts for species identification.

A plan of 3D digital imaging, conservation, and storage was developed to record, study, and preserve the wooden and ceramic material. As soon as wood was removed from the water, the wood was kept wet, either in Ziploc bags filled with water or in plastic containers filled with water. The artifacts were photographed, measured, and drawn, and the data were recorded at a lagoon lab or at the field camp. Artifacts of interest made from wood or pottery were 3D scanned at the field lab at night at our base station, some 15–20 km distant by boat. Three-dimensional scans were also made of chert stone tools and jadeite artifacts (McKillop and Aoyama 2018; McKillop et al. 2018). Selected objects were exported under temporary export permit from the government of Belize for conservation, using the polymer method, to Texas A&M University (Smith 2003). Wood post samples were exported for species identification and radiocarbon dating. Selective pottery sherds were exported for specialist analyses, including petrographic study. All artifacts for export that were stored in water at our field camp were removed from their containers and wrapped in plastic wrap, and placed in Ziploc bags for shipping. On arrival at the archaeology lab at Louisiana State University (LSU), most objects were placed in labeled plastic containers filled with fresh water to preserve the integrity of the objects and to begin desalination. Some wood and pottery sherds were wrapped in plastic wrap and refrigerated, to compare this method of preservation with storing objects in water.

Wood artifacts and posts covered in plastic wrap and refrigerated preserved better than samples placed in containers of water (McKillop 2019b). A sample cut from the top of a palmetto palm post (*Acoelorrhaphe wrightii*), covered in plastic wrap and refrigerated for 13 years, was well-preserved. In contrast, there was abiotic decay of the wood samples stored in water over the same time. Water saturates the cells, lignum, and other structures of the wood, expanding and collapsing the species-specific features of the wood structure. Decay of the internal structure of the wood is a problem for identification of tree species, which is accomplished by viewing razor-thin slices of the transverse, tangential, and radial views of wood with a microscope or scanning electron microscope (Robinson and McKillop 2013). The surface digitizer, and the Matter and Form scanner. Inexpensive scanners such as the Sense and i-Sense provide low-resolution imaging suitable for teaching or displays, including head and full-body scans (McKillop 2016).

More expensive laser scanners with higher resolution include the Faro, Smartscan, Creaform, Minolta Vivid 9i, Microscribe with Kreon laser scanner, and Artec scanners. The hieroglyphic staircase at the Maya city of Copan, Honduras (Tokovinine 2013; Fash 2012) and a building façade at Holmul, Guatemala (Tokovinine and Estrada-Belli 2017) were imaged using the Smartscan. Artec produces 3D scanners (Space Spider, Eva, and Leo, among others) that are faster than the NextEngine and have higher resolution (McKillop and Sills 2019).

In contrast to laser surface scanning, photogrammetry uses still images with significant overlap to produce a 3D digital image of an object. Photogrammetry is popular in archaeology because of the low cost, high-quality color, and good results. Although a cell phone or point-and-shoot camera can be used to capture photos, a DSLR camera arguably provides better results. Photoscan Pro is the common software used to build the 3D image. Photogrammetry is also being used to record excavations in 3D, overlapping with stationary LiDAR in the ability to digitally record large objects, caves, and buildings in high-resolution 3D (Weber and Powis 2014). Airborne and stationary LiDAR (Chase et al. 2011) extend the scale of desktop and handheld 3D scanners to buildings, sites, and the landscape.

Description of the NextEngine and the Scanning Process

Successful use of the NextEngine 3D laser desktop scanner in labs and during field research depends on knowledge of the specifications of the hardware and the ScanStudio software, as well as use of a computer with a dedicated video card with at least eight GB of RAM, and a hard drive capable of storing large digital files. Scanning objects on automatic settings produces variable results. Manual scanning allows the user to push the limits of the hardware and software to produce better 3D scans. The NextEngine consists of a scanner with a still camera for taking photos of each scan, and laser scanners to capture 3D digital data in a line-of-sight view. The scanner is attached to a computer via a cable and must also be plugged into an electrical outlet. A scanning base is attached by a cable to the scanner. The scanning base has an adjustable platform for placing the object to be scanned. The platform is attached to a metal rod placed in one of four holes in the scanning base. The metal rod supports an adjustable arm to hold the object in place on the platform. It is important to change the location of the metal rod periodically to

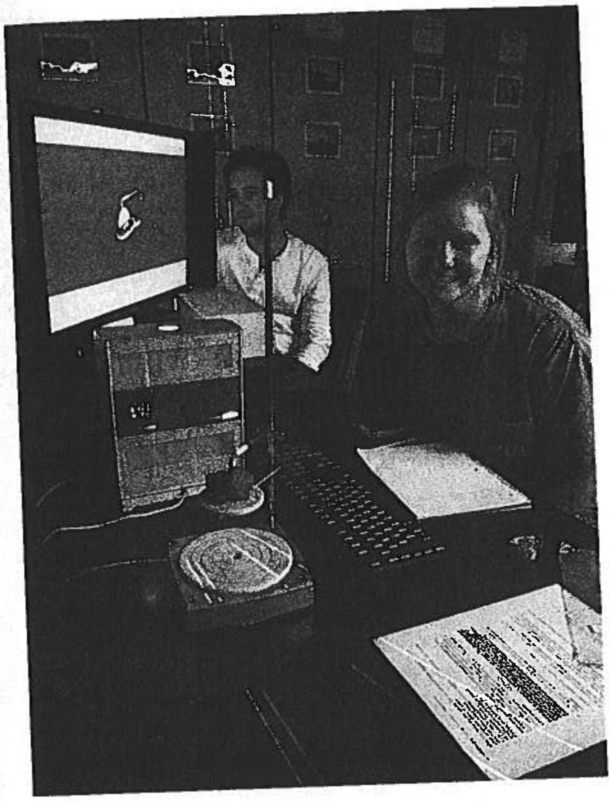

Figure 13.2. NextEngine 3D scanner in operation.

avoid excess wear and weight on one area of the base, which can cause a corner to lift and require a new base to be purchased. Putty can be used to hold the object at desired angles for scanning instead of using the adjustable arm.

There are three distances at which the scanner can be separated from the center of the scanning base for optimal results, depending on the size of the object to be scanned. Small objects (such as a small sherd) are scanned on macro view, at an ideal distance of 11.5" (29 cm). Larger objects (such as a pot or stone tool) are scanned on wide view, at an ideal distance of 21" (53 cm). Extended view is for larger objects (such as a post), at a recommended distance of up to 30" (76 cm). However, the 4'7" (1.43 m) K'ak'Naab' canoe paddle was scanned at a greater distance on extended view. The paddle was placed on a counter in the lab without using the scanning platform. A distance is acceptable when the object to be imaged is in focus and in view when rotated 360 degrees (using the arrow keys on the screen) in the scanning window in the NextEngine ScanStudio software on the computer's monitor. By left-clicking on the mouse and drawing a box around the scan area on the monitor, the scan can be limited to the object to be scanned.

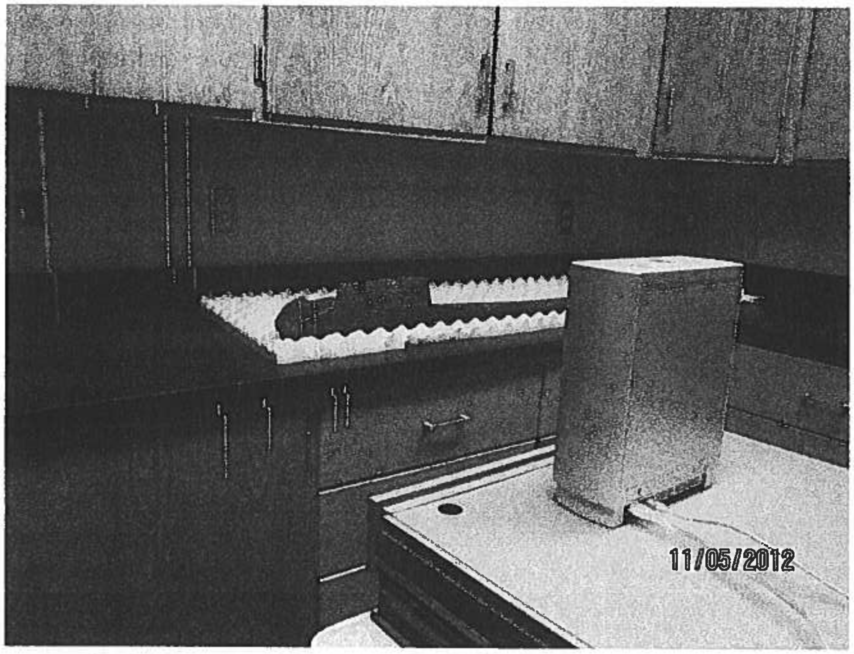

Figure 13.3. NextEngine 3D scanner imaging 4'7" (1.43m) Ka'ak'Naab' Maya canoe paddle without cable. (Scanning by E. Cory Sills.)

There are three ways to image an object, including a 360-degree rotation, a single scan, and a bracket scan, each referred to as a scan family. Most objects are imaged using a 360-degree scan family, with a second 360-degree scan family used when one places the object in such a way as to view the areas blocked by the platform and scanning arm in the first scan. Doing two 360-degree scan families produces duplicate digital scan data that can result in large scan files. Using a couple of single scans or bracket scans to capture areas missed on an initial 360-degree scan reduces file size and the time required to scan. Another option is to remove data by trimming duplicate scan data or by removing individual scans from a scan family. An individual or bracket scan must include a view of other scans so that they can be aligned, rather than including just an uncaptured view of the object (such as the edge of a sherd or base of a stone tool). Each of the scan families, whether 360, single, or bracket, is saved by the ScanStudio software in its own folder on the computer. Each scanned object has a separate folder containing all the scan families.

For a 360-degree scan, the base platform moves several times, according to user selection. Each scan is line-of-sight, and overlaps with the previous scan so images can be aligned. The number of individual scans (which are termed divisions) in a 360-degree scan family can be adjusted from four to twelve. The more divisions there are, the more overlap there is, and the higher the resolution will be; more divisions also mean more time will be required to scan one complete rotation or scan family. Using a higher number of divisions may crash a computer, depending on its RAM. A starting point for scanning is five to six divisions using two 360-degree scan families.

Point density is set from low density to standard density to high density, with the number of points per square inch increasing accordingly. A scan using a high-density setting with 12 divisions will take longer to execute than a 360-degree scan with lower density and/or fewer divisions. Generally, high density with a lower number of divisions produces a high-quality image. The amount of time required to image an object is shown on the screen. The color of the object is set from dark to neutral to light, with neutral the standard setting.

The scan should be saved after the first scan family is completed and again after each stage in post-processing. Saving a scan while the first scan family is in progress can destroy the color capture and result in a black or purple image. Saving a scan after trimming, aligning, and fusing allows the user to return to an earlier stage without losing the entire scan. A back-up of all raw scan data (called my3D) is automatically saved by ScanStudio on the hard drive. Backup scan files should be removed periodically to free up disk space.

Excess data, including the scanning platform and point gripper, are removed from each scan family using the trim function. Several tools, including a brush, shapes, and digitizing tool, are available to trim all excess data from the raw scans. Using the scroll and rotate function to enlarge and view the 3D scan from different angles on the screen is useful for trimming. The scan should be saved before proceeding to the align function.

The different scan families produced in ScanStudio are joined using the align function. The scanned object from two scan families is viewed side-by-side on the screen. Colored dots are digitally placed in the same place on an object produced from two scan families. If more than two scan families are used, they are added one at a time. Dots help the software join up the scan families, so placing dots in all areas of an object and on different sides is important. Generally speaking, at least six dots should be used—more if the object has a complicated shape. Viewing the scans without color can aid in placing dots. The aligned scan should be saved before proceeding to fuse.

The fuse function produces a smooth exterior surface view in 3D. Small holes can be filled automatically in fuse; using the auto-fill function may flatten the surfaces of larger holes, however, so that should be avoided (this underscores the need to obtain good scans). Checking the "watertight" box is

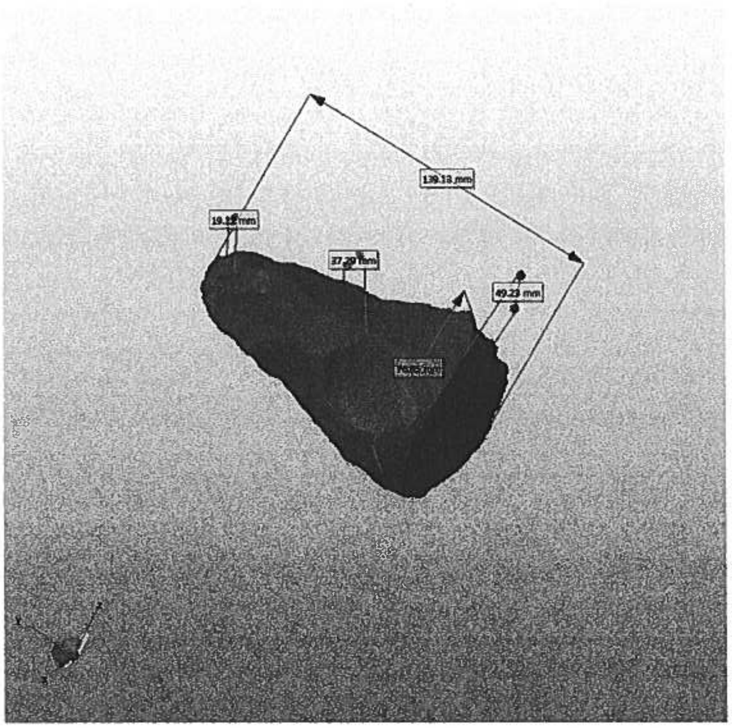

Figure 13.4. Digitally measuring 3D digital scanned chert stone artifact.

essential to producing a 3D image lacking surface holes so that the scan can be printed. Options for saving the file include a variety of file extensions that are used for 3D printing and to manipulate the files in other software programs (STL, WRL, OBJ and PLY formats), in both millimeters and inches.

Although the NextEngine is packaged with ScanStudio ultra HD software, purchasing ProScan provides faster scans with higher resolution. Once the object has been scanned and has been saved as a 3D file (in STL or some other file type), the file can no longer be viewed in ScanStudio. The file can be imported to 3D printer software and viewed before printing. Other software programs used in the DIVA Lab include Rhino, Avizo, Meshlab, Blender, Geomagic (now Geomagic Wrap, Geomagic Design, and other modules), Netfabb, X3Dom, and Adobe360. Open-source software includes Meshlab, which can be used to repair and clean 3D scans and to measure objects. Rhino is useful software for manipulating 3D scan STL files and also for creating short movie clips that can be inserted into presentations or websites (see McKillop 2016). Netfabb, Meshlab, and other programs can be used to digitally measure objects scanned by the NextEngine, with results comparable to the measurement of the actual object (Harrington and McKillop 2015, 2017).

3D Scanning in the Field

Artifacts and wooden posts recovered from seafloor surveying and from underwater excavations at the Paynes Creek Salt Works were 3D imaged using two NextEngine desktop scanners powered by a generator in the evenings during field research in 2012 and 2013, and during two additional lab seasons in a remote location in Belize (2015, 2016). The raw scans were not post-processed in Belize so that data capture could be maximized. Post-processing involves digitally trimming excess data, aligning scans made of the objects from different angles, and fusing scans to make a watertight digital object (in which the surface is devoid of holes). 3D scanning in the field was slow, disrupted by use of a generator that needed to be fueled periodically. Since post-processing of the scanned data was done later, errors or areas missed during scanning could not be fixed.

In 2019, an Artec Space Spider was used to image about 250 artifacts in the evenings after field work. The Artec is faster and has better color than NextEngine, but is significantly more expensive. The Artec 3D scans were postprocessed within minutes to reveal a 3D model. Although it is possible to image an object by rotating the scanner around it, a better method is to use a manual or automatic turntable to rotate the object, and keep the scanner static.

Teaching 3D Digital Imaging

Using skills to successfully 3D image Maya artifacts with NextEngine scanners, a course called 3D Digital Imaging was introduced in the fall semester of 2015 at Louisiana State University. A room in the DIVA Lab was used for instruction, with 10 NextEngine scanners and 10 computers. The first objective of the course was to provide students with the skills to do 3D digital scans of a variety of objects that featured different problems, such as thin and shiny objects, interior spaces, decoration, large objects, and objects requiring specialized knowledge for study. The second objective was for students to learn how to evaluate options for 3D imaging when presented with a new object. A third objective was for students to learn how 3D surface scanning and photogrammetry are used in archaeology. A fourth objective was for students to evaluate the parameters of 3D surface scanning and photogrammetry for the application of various open-source and proprietary software

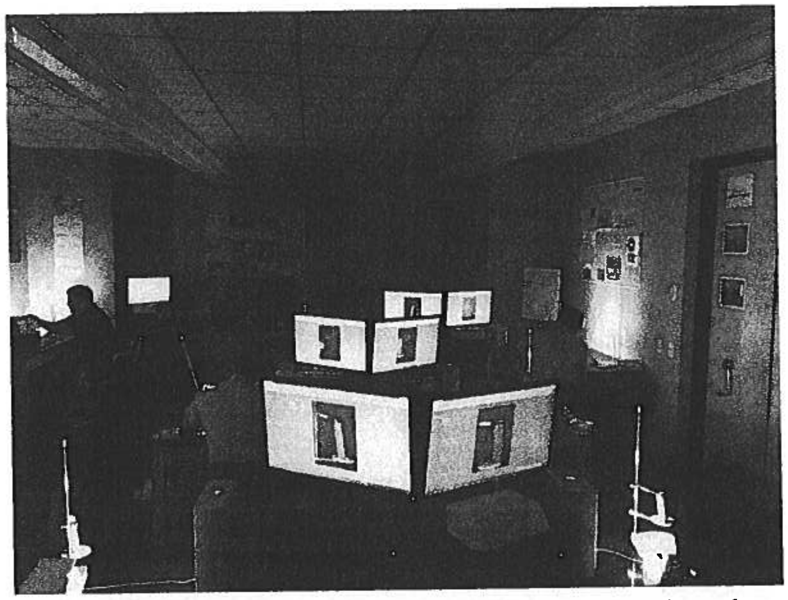

Figure 13.5. NextEngine 3D scanners in classroom, with laser scans directed away from students.

programs to analyze and to prepare for 3D printing. A fifth objective was for students to integrate 3D imaging into research through their course project, lectures, and discussion of assigned articles.

Lectures and discussion of articles tie the course to the 3D digital imaging and printing being carried out. The course is lab-focused, with ten exercises on different materials featuring various challenges that increase in difficulty over the semester. Students are encouraged to add photos (JPEG images taken from the scanner before each individual laser scan or snipped images students take while scanning) to document the scanning process, errors, and techniques. Artifacts and 3D-printed replicas from the Paynes Creek Salt Works are used, with students agreeing in their syllabus that their scans may replace existing scans of objects if theirs are better quality. Using 3D-printed replicas of artifacts made with the DIVA Lab's color gypsum 3D printer protects the original artifacts.

The course begins with two weeks of lectures, providing an overview of 3D imaging in archaeology. On the first day in the lab, students learn how to use the hardware and software by scanning an undecorated potsherd, following instructions on a lab form to select two 360-degree scan families at five divisions (Table 13.1). For exercise 2, students follow similar instructions for scanning a decorated pottery sherd. In addition, students read about the pottery type, the location of the UTM coordinates for the site (and what the

Table 13.1. 3D digital imaging lab exercises for learning surface scanning

Lab exercise	Assignment	Rationale
	Drawing a potsherd	Not everyone can draw
1	3D scanning a potsherd	Learning the basics of NextEngine
2	3D scanning a decorated potsherd	Capturing color and incised decoration
3	Briquetage! (salt-making pottery)	Larger objects and different shapes
4	Stone tools; Netfab.com	Shiny and thin objects; Learning to measure objects digitally
5	Creating a web page (wix.com)	Each student posts academic CV and space for weekly blogs
6	Boat model	Scanning interior space
7	Maya ocarinas (course project)	Complex objects with interior space
8	Waterlogged wood post	Fragile, dark, wet objects
9	Bone	Knowledge of bone features important
10	Photogrammetry; Photoscan Pro	Photographs of ocarina, post processing

Universal Transverse Mercator grid is), and draw their potsherd. Students become familiar with the catalogue system used for the Paynes Creek Salt Works project.

Subsequent exercises challenge students to decide how best to scan various objects. For exercise 3, each student is asked to use individual judgment to scan two pieces of briquetage, including a large rim sherd and a clay cylinder vessel support (McKillop and Sills 2016, 2017). The cylinder presents a challenge, since the complete object can be imaged in one 360-degree scan family, except for each end. A second 360-degree scan produces duplicate digital data. Doing a 360-degree scan of the cylinder, followed by a single scan or bracket scans of each end, requires less scanning time than a second 360 scan and results in less duplicate digital data. A workaround is to use putty to elevate the cylinder end so it, as well as part of the side, are visible; this is necessary because common points are needed to align separate scans.

Exercise 4 introduces students to the problems inherent in imaging a thin, shiny chert artifact. Shiny objects reflect the laser, resulting in lack of data. Reflective objects can be powdered using the powder brush that comes with the NextEngine kit. The NextEngine is not good at aligning thin objects. In order to scan thin objects successfully, blocks of putty can be placed at each end of a stone point, making sure the putty extends at least one-half inch beyond the end, essentially tricking the scanner into thinking it is scanning a wider object. This exercise marks the point when students are told to experiment and that it is okay if the scan does not work out. They are encouraged to look at other students' scans to see the range of methods and results, including split images in the scan families, holes from reflective surfaces, and scan families that do not align along sharp edges.

In the next exercise, each student makes a web page to provide a platform for each to write four blog reports on an artifact assigned for their course projects. In order to give students a web presence that will allow them to present their research in the public domain without requiring them to learn to code, they use Wix.com, a free, preformatted website service that assigns each of them a web page. They also create an account on Sketchfab so they can upload scans and link them to their web pages.

For exercise 6, students image 3D printed replicas of a small boat model, which provides the challenge of scanning an object with a partially hidden concave space on the NextEngine scanner. An added level of difficulty is that some of the replicas have a white, reflective surface that may require a change to the settings.

The course project is introduced in an exercise for which students are instructed to use their learned skills to figure out a scanning plan, and to take notes and photos or snip images on their progress. Each student is provided a Maya ocarina from the Paynes Creek Salt Works, with a catalogue number. Graduate students are assigned a more difficult object to scan, or two objects. The skills developed in the earlier exercises are intended to provide some background to help students scan interior spaces, complex shapes that include areas hidden from the line-of-sight view of the scanner, and odd shapes. Beginning with the ocarina scan exercise, students are required to write four weekly, 500-word blog reports on their web page, with the first report to be posted to their web page each week. Assigned topics include the ancient Maya, methods used to scan the ocarina, background on Maya ocarinas, and interpretation of the student's ocarina. Students are encouraged to use their blogs to research and write their term PowerPoint presentations and reports, due the last week of class. Articles on Maya ocarinas are assigned for reading.

For exercise 8, students scan the sharpened end of a wooden post fragment from the Paynes Creek Salt Works (McKillop 2005). In addition to having sharp edges and a dark color, the posts are waterlogged. They are stored in plastic containers on a table in the lab. Students need to remove the post, dry it with paper towels, image it, and replace it in the container of water.

Exercise 9 consists of 3D-imaging a bone. The Maya skeletal material used in research and instruction in the LSU DIVA lab was exported under permit from the Belize government Institute of Archaeology, which receives digital and printed copies of publications, theses, and dissertations on the material. Students are provided with relevant literature on human osteology and asked to identify the bone and the important features that allow the bone to be identified. Part of the exercise is learning that to conduct a successful 3D scan, the person needs to know how to scan and have prior knowledge about the skeletal material.

The assigned articles are about 3D surface scanning and CT scanning of bone, as well as the ethics and value of imaging human skeletal material. The practice and value of 3D imaging human skeletal remains must be measured against legal and ethical issues. Three-dimensional imaging of human bones allows researchers to enlarge material and obtain more accurate measurements (Harrington and McKillop 2015; Harrington 2017; Kuzminsky and Gardiner 2012; Wroebel and Hair 2019). Accurate 3D scans of bones can be used for research and instruction, protecting the integrity of the original, similar to the use of casts. Scans can be digitally shared to facilitate study. The 3D imaging of human bones is regarded as valuable for research in biological anthropology, bioarcheology, and forensics, for instruction, and for applications in the medical and dental fields. However, consideration of legal and ethical issues pertaining to the 3D imaging of human skeletal remains has become a topic of considerable discussion (Bouton 2018; Jani et al. 2020; Smith and Hirst 2019; Wild 2020). NAGPRA in the United States and antiquities laws in other countries may restrict the study of human skeletal remains, including their 3D imaging (Bouton 2018). The San Diego Museum of Man requires informed consent of descendants or communities. Some online repositories, such as Morphosource, restrict access to human skeletal material and only display it when consent documentation is available. Other online repositories allow the viewing but not downloading of 3D images, including eAnthro.org and Skeleton.org (Smith and Hirst 2019; Wild 2020).

In the final exercise of the course, students learn photogrammetry and compare it with 3D laser scanning. Students take turns using a Canon DSLR camera on a tripod to take photos of their ocarina while it rotates on a turntable. Students take overlapping photos at the same distance from the ocarina while rotating the turntable, starting at the top of the object and moving down in rows. Then the ocarina is turned so that the parts that were not initially visible can be photographed. Students upload their photos to PowerPoint and delete images that are out of focus or redundant, each student ending up with 80–100 images on average. Using the "remove background" option in PowerPoint, the background is removed from each photo and the file is saved. The images are then uploaded to Photoscan Pro, which is available under site license to LSU, to continue post-processing.

Storage, Archiving, Inventorying, and Accessing 3D Digital Data

As well as creating accurate 3D images, students were taught that it is useful to develop a plan for digitally archiving raw data and scans in various formats and sizes to suit different needs, including for research, teaching, and outreach as well as for 3D printing (see Richards-Rissetto and von Schwerin 2017). In the DIVA Lab, raw scan data and completed STL files were stored on portable hard drives. As the number of scans and variety of formats increased, a storage and retrieval plan was designed. The 3D scan files are stored remotely on an 8TB hard drive that can be accessed via the internet. This includes an inventory of all raw scan data and completed scans recorded on an Excel spreadsheet, along with a 2D photo created by ScanStudio during scanning. The Excel spreadsheet includes the scan file name, site number, project or topic, file type, name of the scanner, and location(s) of the data. With the added photo, the Excel file is large and cumbersome. In addition to the basic 3D scan data, additional files include completed 3D scan files saved in up to four formats in both millimeters and inches, files downsized to print, and 3D printer files at actual size and other sizes (smaller or larger).

Sharing 3D scans involves opening the file in a software program that accepts 3D files, which is a constant challenge for viewing and sharing large files. In order to view completed 3D scans created using the NextEngine software ScanStudio, other software is required, since ScanStudio does not have an option to open and view completed and saved 3Dscans. Scans can be imported to Sketchfab, Rhino, Adobe3D, X3Dom, Blender, Aviso, Geomagic Wrap, Geomagic Design, and other programs. Scans uploaded to Sketchfab can be shared online (McKillop 2016). Adobe3D and X3DOM are used to transform scans to formats that can be viewed or shared. Scans transformed in Adobe3D are viewable PDF files that can be resized and rotated by the viewer. Scans imported to X3DOM can also be viewed and rotated by the viewer. Rhino is used to create film clips that are shared and posted online or used in teaching or conference presentations (McKillop 2016).

Uses of 3D Technology in Archaeology and Heritage

Teaching 3D digital imaging in a research lab with 3D printers provides an opportunity for students to learn about 3D printing and sometimes to print their scans. One semester, students in the 3D digital imaging course participated in 3D printing their project ocarinas. This required expertise beyond the course, money for 3D printing materials, and additional time that conflicted with students' other courses; all this resulted in grad students doing most of the 3D printing. Students supplied their watertight 3D scan files, but those needed to be downsized (using Avizo or Meshlab software) in order to be printed. Scans can also be downsized during scanning by cutting away the excess data resulting from imaging the same area multiple times. Overlapping scan data are produced that feature multiple divisions within a scan family and with additional scan families of multiple divisions or single or bracket scans. By clicking on the scan family icon once the scanning is complete, the individual five to 12 scans in a scan family can be viewed, and duplicate data deleted or trimmed away.

For the 3D printing, students provided their scans in two formats, including STL files and WRL files. The STL files are used with the Dimension Elite 3D printer in the additive process of using ABS+ model material and support material to build the object. This requires removing the support material from the 3D print in the heated, chemical bath. Both 3D printers take more time than was provided during the course. Students provided WRL files to

Figure 13.6. Three-dimensional printed bust scanned from Sense scanner shows value of low-cost 3D scanner for display purposes.

make photorealistic 3D prints using the ProJet 460 3D printer, which injects color and an adhesive in layers to outline the exterior of an object in a bed of gypsum powder. The resulting 3D print is then produced by vacuuming the powder, brushing the exterior, and then immersing the object in a solution that solidifies the surface. Although several scans could be printed at the same time on each 3D printer, the printing and post-processing took much longer than the time allocated for classes, and thus required the assistance of several graduate students proficient in 3D printing. Showing students the process of 3D printing is valuable, but with the time constraints of a course, students are generally provided with options for 3D printing elsewhere, such as at public libraries. DIVA Lab scientists, including undergraduate student workers and graduate students who work in the lab, learn 3D skills by practicing. Some students develop 3D projects for theses or dissertations, and present at conferences.

3D Printing for Research, Teaching, and Exhibits

Some 3D scans meet the standard for teaching and/or displays but not for research. Sharp edges and concave shapes do not always image well using the NextEngine. Similarly, closely spaced teeth in a mandible or maxilla are not separated in the digital image. A sample of skeletal remains from the Maya site of Moho Cay, Belize was found, in terms of comparison of features on the bones with the 3D scans, to be of display or teaching value instead of research quality (Harrington and McKillop 2015). Hip bones from an adult male and an adult female were imaged for use in teaching human osteology in an Introduction to Archaeology class; the 3D scans could be rotated and moved on the projector screen, providing a better view of the features that

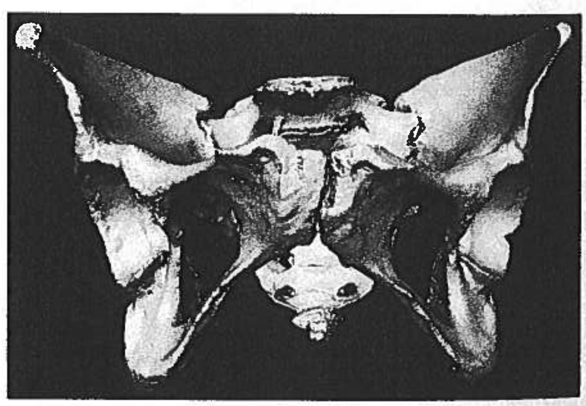

Figure 13.7. Three-dimensional scan of hip bone from adult female done with NextEngine, using 12 divisions and high density, showing the value of such items for teaching. (Scan by Victoria Harrington, Louisiana State University.)

distinguish the hip bones as male or female than would a static image on a screen or actual specimens in a large lecture hall.

Discussion

Learning the technical skills required of 3D imaging prepares students and others to incorporate 3D scans into cultural heritage research, instruction, and outreach (as well as many other applications). Some of the technical skills include knowing the parameters of scanning hardware and software, knowing diagnostic features of different materials, such as muscle marks on bones or the edges of stone tools, and knowing how to evaluate the accuracy of 3D scans. Research in the DIVA lab by faculty and students includes a variety of digital projects that use 3D imaging. Hundreds of potsherds, stone tools, wood posts, and other objects have been 3D-imaged using the NextEngine and, since 2019, an Artec Space Spider. Most of the scans are from the Paynes Creek Salt Works (McKillop 2016). The 3D digital record is used for artifact classification, for taking measurements of size and volume, and as examples for presentations and publications.

Three-dimensional printed replicas of artifacts have been used for temporary displays at the Baton Rouge Maker-Faire, a display at the LA State

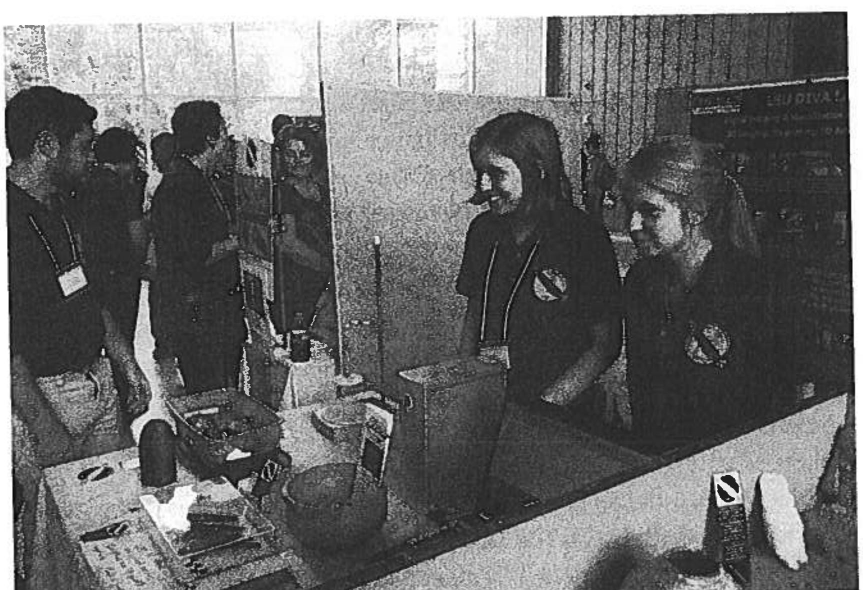

Figure 13.8. Replicas of artifacts scanned with NextEngine and printed in ABS+ plastic at an outreach event at the Baton Rouge Maker-Faire, October 2015, showing the value of such items for exhibits and teaching.

Museum, Fall Fest events at LSU, Graduate Student Fairs at LSU, and an LSU Library event, among others, attesting to the value of and interest in 3D printing for public outreach. A long-term display in a hallway cabinet in the foyer of a building at LSU focuses on a full-sized, 3D-printed replica of the K'ak'Naab' Maya canoe paddle, which is 4'7" in length. In addition to the 3D print, a modern version of the canoe paddle is displayed, showing the original shape with the blade on both sides. There is also a TV monitor with a rotating set of images, as well as laminated posters with images and text explaining the discovery, conservation, 3D scanning and 3D printing, and interpretation of the canoe paddle.

Some DIVA Lab projects use 3D representations to replace 2D drawings of artifacts or bones (Fiegel 2018). In an ongoing project, 3D scans of large potsherds were imported to Rhino software to reconstruct vessels (McKillop and Sills 2013a, 2013b; Vines, McKillop, and Sills 2014). Scans of human hip bones using different point density and numbers of divisions in a 360-degree rotation were compared with the bones themselves to evaluate the accuracy of the digital representations (Harrington and McKillop 2015, 2017). Mid-range to high-range settings for point density and number of divisions rendered the highest accuracy, with over 95% similarity between measurements and observations on the digital and actual bones. Digital measurements on the scans were compared with bone measurements. Categories of display, teaching, or research value were assigned based on the degree of similarity of measurements.

Exhibits created using 3D-printed replicas of artifacts from the Paynes Creek Salt Works aim to engage the local population in the preservation of the archaeological sites by creating tourism destinations (McKillop and Sills 2013a, 2013b). Permanent exhibits featuring 3D-printed replicas of artifacts and wooden posts from the underwater sea-floor survey and excavations at the Paynes Creek Salt Works were set up in the Toledo District capital of Punta Gorda, Belize and at the Paynes Creek Ranger Station (Figure 13.9). The exhibits feature 3D prints in display cases along with laminated posters explaining the sites and artifacts. An additional exhibit was placed at the Paynes Creek Ranger Station at the request of marine tour guides, who want to increase tourism.

Using 3D-printed replicas of artifacts for exhibits has several benefits over using artifacts themselves. The 3D prints have no value on the international antiquities market, so the exhibits do not require the additional security necessary for artifacts. The 3D prints do not require an artifact loan from the Belize government, which extends the potential to place exhibits in other locations, and allows communities to imitate such exhibits. Ocarinas and other

Figure 13.9. Exhibit in Punta Gorda, Belize, featuring 3D-printed and -painted replicas of artifacts from the Paynes Creek Salt Works, along with laminated descriptive posters and signs, showing the value of 3D scans and prints to cultural heritage.

small objects can be 3D-printed larger than actual size, which enhances visibility in an exhibit. The 3D prints are good replicas that some viewers may think are the actual artifacts. The full-sized (4'7") replica of the Classic Maya canoe paddle (McKillop 2005) was widely viewed as the original paddle.

Use of 3D technology in the Maya area to document, analyze, and communicate through outreach and instruction includes LiDAR, photogrammetry, 3D laser scanners, virtual and augmented reality, and 3D GIS. Airborne LiDAR was used to digitally remove the rainforest at Caracol to reveal the stone building remains of the large urban city that had stood there (Chase et al. 2011). Airborne LiDAR in Guatemala and near Mayapán, Yucatán, Mexico, shows a bare-earth surface, making it possible to study settlement, defensive systems, and population size and density (Canuto et al. 2018; Hare, Masson, and Russell 2014). Stationary LiDAR records buildings exposed during excavations at Pacbitun, Belize, and the site inside the cave at Las Cuevas, Belize (Moyes and Montgomery 2016; Weber and Powis 2014). Reconstructed views of buildings in their environmental setting at Cerros, Belize used augmented reality to create views of past settlements (Vadala and Milbraith 2016). The 2D GIS maps of posts at the Paynes Creek Salt Works were extruded using post diameters in order to build a 3D GIS of the area (McKillop and Winemiller 2021). Airborne LiDAR data and GIS from Caracol are used to analyze settlement and household water storage at Caracol (Chase 2016, 2017). Photogrammetry is used to document excavations (Novotny 2019), record human crania (Wroebel et al. 2019), and document artifacts. SmartScan was used to image the hieroglyphic staircase at Copan, Honduras, as well as other stone monuments (Tokovinine and Estrada-Belli 2017). In addition to the Paynes Creek Salt Works (McKillop 2016; McKillop and Sills 2013a, 2013b), researchers at Cerros (Walker 2016; Walker and Milbraith 2012) and elsewhere (Fiegel 2018) are using the NextEngine and other 3D laser scanners to produce 3D digital replicas of artifacts.

Future directions include more use of 3D scans of artifacts for analyses, such as the comparison of pottery ocarinas and molds by Winemiller et al. (2018); digital measurement of artifacts (Shott and Trail 2012); reconstruction of pottery vessels from potsherds (Bowen 2021; Vines, McKillop, and Sills 2014); and analyses of spatial 3D data (Chase 2016, 2017). The use of 3D-printed replicas of artifacts in displays (McKillop and Sills 2013), replicas that can be held and touched in museums (Cooper 2019), and 3D replicas of musical instruments that can be played (Katz 2017), instead of actual artifacts, will extend access to the past for outreach and instruction. Researchers from the Smithsonian worked with the Tlingit First Nation on Canada's northwest coast to provide them with 3D images of headdresses. The Tlingit started 3D printing their own from 3D files, and some have been used in ceremonies in cases where the original headdress has been lost or damaged. The 3D-printed replicas became the real masks (Mendoza 2015). In a similar way, the 3D-printed replica of the K'ak'Naab' Maya canoe paddle on permanent display in an exhibit case (McKillop and Sills 2013a, 2013b) has been interpreted as the real canoe paddle by viewers in Punta Gorda, Belize. In both cases, the high-quality 3D scans produced actual-size 3D-printed replicas intended to be identical in appearance to the originals.

Virtual sites with structures, artifacts, landscape, and people (Vadala and Milbraith 2016), publication of 3D images in journals and digital books, as well as digital publications featuring 3D sites, are likely extensions of 3D reconstructions of Maya sites and artifacts shared on social media and web pages. As 3D technology becomes less expensive and more accessible to archaeologists, as more students learn 3D skills, and as digital publication platforms become more readily available, the growing body of 3D images will reach a wider academic and public audience (Katz and Tokovinine 2017; Rick 2012). 3D digital images provide new opportunities for measuring, sharing, and contextualizing the past (Katz 2017; Magnani 2014; Orpitz et al. 2016; Vadala and Milbraith 2016; Winemiller et al. 2018).

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