A Virtual Paleolithic:
Assays in Photogrammetric Three-Dimensional Artifact Modelling

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ABSTRACT

Access to Paleolithic artifact collections is often constrained due to the cost of travel, governmental restrictions, and the rare nature of unique specimens. In the current high-tech climate, researchers are turning their attention to alternative ways of gaining information about and analysing these materials. The recent boom in three-dimensional replication of cultural materials including lithic, bone, and fossilized specimens, has provided researchers with an invaluable analytical tool with which to carry out new and innovative studies. In this paper, the authors review a cost-effective, photogrammetric-based three-dimensional modelling system that utilizes digital artifact images and commercial software. Requiring only a notebook computer and standard digital camera, this methodology allows for the production of digital computer models from which important morphological information can be obtained. The modelling process is exemplified through two case studies—the replication of an Acheulian handaxe and the ongoing modelling and analysis of Middle Paleolithic refitted cores from the site of Taramsa Hill, Egypt. In both cases, the forensic software package *iWitness*™ was used to identify points on the artifact surface that were then converted into points in three-dimensions. The wireframe models produced from these points were then imported into *3DS Max 9*™ where the model was skinned and subsequently manipulated to produce cross-sections and calculate morphometrics such as surface area, volume and center-of-mass. Aside from the analytic advantages it affords, three-dimensional modelling ultimately provides the opportunity for increased sharing of data, ideas, and results among members of the geographically distributed paleoarchaeological and paleoanthropological community. Digital models can be sent electronically via the Internet without the restrictions typically associated with valuable archaeological specimens. Photogrammetric modelling methods are ideal for this purpose because the images required to create virtual models can be easily obtained from collaborators worldwide and subsequently processed in a location of the researcher's choosing. Consequently, photogrammetric three-dimensional modelling represents a useful and accessible alternative to more expensive laser scanning technologies.

INTRODUCTION

The use of three-dimensional modelling in archaeological analyses has become increasingly popular over the last decade. At the recent 2007 Society of American Archaeology Annual Meeting in Austin, Texas, an entire pre-conference session was dedicated to the range and uses of three-dimensional scanning techniques in archaeology. The growing interest in such approaches stems, at least in part, from the increasing accessibility of modelling technologies. Not only have a wide range of commercial alternatives become available in recent years, the declining cost of these technologies has made three-dimensional modelling more accessible to researchers. With technological literacy at an all time high, archaeologists are more than ever taking advantage of this promising analytical and illustrative tool. There are, however, challenges to integrating these kinds of methodological approaches into one's research program. Mafart (2002) points out in his review of the extensive colloquium concerning three-dimensional imaging in archaeology at the XIV UISPP Congress:

> "In prehistoric archaeology, image acquisition often requires a skilful technician able to adapt industrial surface scanning techniques to archaeological soils or objects, the services of a computer technician, and the cooperation of the team in charge of the archaeological site. The level of technical complexity is such that no investigator can have the full range of competency and yet each must know and understand the roles of the other players"(1).

While this may be true in some circumstances, it is demonstrated here that the skills and knowledge required to model archaeological specimens can, in fact, be acquired and applied within a reasonable period.

Three-dimensional modelling has been applied to a multitude of archaeological research programs at varying scales of analysis, from individual artifact reconstruction (Schurmans et al. 2001) to virtual site reproduction (Zabulis et al. 2003). The range of materials examined in these studies include, but are not limited to, stone (Boehler et al. 2003; Riel-Salvatore et al. 2002), bone (Mafart et al. 2004;

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Rosenberger and Hogg 2007; Wood et al. 1998), ceramic (Kampel and Sablatnig 2001), and textiles and paper documents (Debevec 2003; Hawkins et al. 2001). Riel-Salvatore et al. (2002) describe a computer-based methodology for the automation of lithic refitting using a laser digitizer to scan flakes from a sample of previously refitted Ahmarian cores. Surface morphologies of the digitized models could then be compared to identify refitting fragments. Clarkson et al. (2006) present a method for quantitative evaluation of flake scar patterns on an artifact by recording individual scar orientations in three dimensions using a stylus-based digitizer. In contrast to two-dimensional approaches for studying surficial scar patterning, this and similar methodologies have great potential for exploring core reduction strategies from a perspective that better represents the non-planar morphology of lithic artifacts. Matusik et al. (2002), and Műller et al. (2005) describe image-based modelling systems capable of replicating detailed objects and materials.

At the macro-scale, three-dimensional modelling techniques can be used to capture site information for the production of visually informative images of archaeological sites. Barceló et al. (2003) describe the creation of digital terrain and elevation models for Shamakush VIII, a shell midden site in Tierra del Fuego, Argentina. With their models it was possible to graphically represent and manipulate strata, providing a better understanding of formation processes that generated the stratigraphic sequences. Losier et al. (2007) apply GPS data to the Gocad modelling tool to produce three-dimensional reconstructions of excavation trenches at the Syrian site of Tell 'Acharneh. Similarly, a combination of photogrammetric and three-dimensional scanning techniques was applied to the mapping of the Pinchango Alto site in Palpa, Peru (Lambers et al. 2007).

In line with the work of Pollefeys et al. (2001), the authors here review their methodology for incorporating photogrammetry with three-dimensional computer modelling to digitally reconstruct Paleolithic artifacts. A comprehensive explanation of the modelling process is provided first, detailing the equipment required and how it was used to create virtual artifacts. The process is further explained through two test-cases—the reconstruction of an Acheulian handaxe and the more extensive application of the process to Sumner's doctoral research on Middle Paleolithic (MP) lithic core reduction. In the final section, the potential for the proposed methodology in Paleolithic research is expounded upon, and it is concluded that photogrammetric modelling is uniquely suited to Paleolithic research because it allows one to create virtual models of specimens that may be inaccessible to the researcher using only digital images.

METHODOLOGY

Photogrammetry involves the calculation of reliable measurements from photographs and digital images. Two common applications for photogrammetry are in the production of maps from aerial photographs or satellite images and the forensic reconstruction of accident scenes. While map production largely involves working in two dimensions, measurement in three dimensions is also possible albeit with the use of more complex mathematics. Provided a sufficient number of images are available, one can determine the shape and relative size of the three-dimensional objects depicted. Further, this information can be used to recreate the form of an object in a virtual environment. The method described here entails the calculation of three-dimensional points on the exterior surface of an artifact. Points are identified from multiple digital images of the same object taken from a variety of incident angles. Surface points are situated in three-dimensional space and can be connected to create a 'skin' that approximates the exterior surface of the object being modelled.

The hardware required for photogrammetric modelling consists solely of a digital camera and a computer. As stated above, all calculations of artifact dimensions are made from images, thus no specialized measuring equipment is necessary. The digital camera is used to capture images of the subject that are then uploaded to the computer for processing. High image quality is preferred, so a digital camera with support for 1024 x 768 or greater pixel resolution is recommended. While SLRs provide superior control over light and focus during image acquisition, a standard point-and-shoot model is sufficient. Traditional film cameras also may be used but typically offer lower resolution and the resulting images are more difficult to transfer to digital form. Although a notebook computer is recommended over a desktop model for ease of transport and overall convenience, it is not a requirement. Both computers and digital cameras are sufficiently commonplace today that their acquisition should come with minimal difficulty and cost to most researchers.

For processing the artifact images, one also requires two computer applications—one for photogrammetric measurement and one for three-dimensional modelling. Several alternatives are readily available on the market. The programs selected by the authors for use here are *3D Studio Max 9* (*3DS*)™ and *iWitness*™. *3DS* was chosen because of the authors' familiarity with the program; however, other commercial applications would also be suitable, including CAD software that supports three-dimensional modelling, such as *AutoCAD*™ and *SolidWorks*™. *3DS* also was chosen for its robust animation features, useful for presentations and other demonstrative purposes. *iWitness* is a photogrammetric modelling program originally intended for forensic site reconstruction. Although not designed with archaeological applications in mind, *iWitness* is a versatile tool that has proven exceptionally effective for these purposes. While one may choose to employ additional equipment for convenience, speed, or other reasons, the aforementioned comprise the bare essentials and include technical resources many researchers can readily access. At the time of writing, the software could be purchased for 1500 USD, including a full version of *iWitness* and a student license of *3DS Max*.

The first step to modelling artifacts in this fashion is the acquisition of subject images. Any object that can be photographed can be modelled. This includes exceptionally large specimens like building architecture and objects as small as microliths. Multiple images are taken of the subject clearly showing all exterior artifact surfaces that one intends to model (Figure 1). Care must be taken to ensure that images overlap to a small degree to allow for the connection of surfaces in the 3D model. Similarly, several images must be taken of the same surface at different angles to increase the accuracy of surficial modelling (Figure 2). How this is accomplished, be it through a selective or systematic process, matters little so long as the above requirements have been met. Accordingly, the number of images needed depends on the size and complexity of the subject. One should keep in mind that, while a greater number of images affords greater model accuracy, it also increases the time required to process those same images. The authors have found that, for most artifact types, having ten to twelve images is usually sufficient for basic modelling purposes. That being said, as few as six images per specimen were used to successfully reconstruct the sample of Middle Paleolithic cores used in Sumner's research. Once acquired, images are transferred to the computer for photogrammetric analysis in *iWitness*.

At the most basic level, *iWitness* allows the user to identify points in the imported images that are common to two or more images (Figure 3). When multiple points have been identified, the distances and angles between points in different images allow *iWitness* to calculate the relative distances and locations of points in three-dimensional space. This process of identifying and tagging points on images is completely dependent on the user, although the program has built-in aids to make the process as accurate as possible. The number of points needed to model an object varies depending on the level of detail one desires to achieve. Identifying more points both increases photogrammetric accuracy (the location of points in space) and provides greater resolution of the artifact surface. Once all desired points have been identified, *iWitness* displays the resulting 'cloud' of points in three dimensions. At this point, the user can join adjacent points with connecting lines, creating a wireframe skin with the same overall morphology of the artifact's surface. The pattern created by connecting lines should create a network of non-overlapping triangles (Figure 4). The model wireframe can then be exported for further modification.

Once the data file has been exported from *iWitness*, it can be loaded into *3D Studio Max*. After being imported, it is vital that the wireframe be examined for flaws in the arrangement of its segments. Segments that do not connect properly with those adjacent must have their vertices moved accordingly. The program makes it possible to connect vertices at precisely the same point in space, thus ensuring a closed wireframe. A common problem encountered in our initial modelling assays was the correction of holes in the model wireframe. When skinned, the model shows regions with missing or erroneous spline connections as gaps in the surface. Minor defects or redundancies in spline arrangement also can be identified in this way. Once all holes have been patched, the surface appears complete and resembles that of the artifact being modelled. At this point one can customize the look of the object's virtual material to resemble any substance, lithic or otherwise. Furthermore, artifact photos can be mapped onto the model surface to give the appearance of the real object.

Two important points regarding how representative the virtual artifact models produced by this method are need to be acknowledged. First, the surface that is produced is a composite of several thousand flat faces created from the spaces between wireframe segments. Minute details of artifact topography, such as cracks, tiny flake scars, and ripples, are not recorded using this method if they exist within these spaces on the actual artifact. Similarly, material texture is not represented except at a very superficial

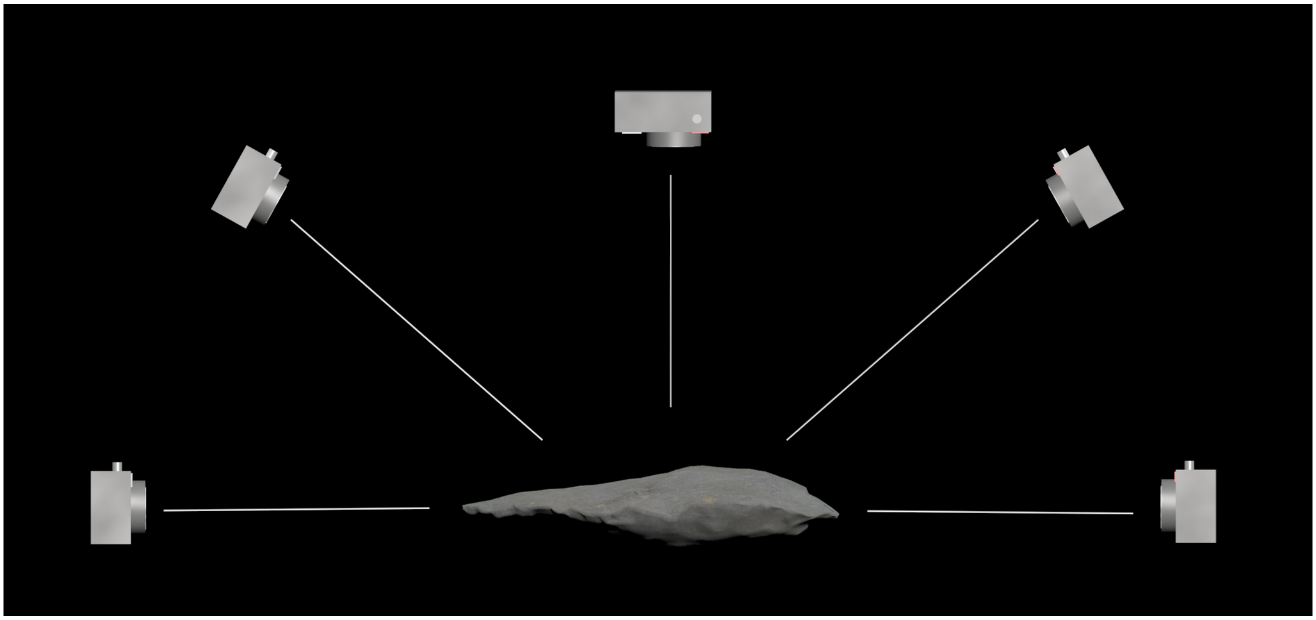


Figure 1. Side view of image capture angles. Oblique angles of approximately forty-five degrees were used.

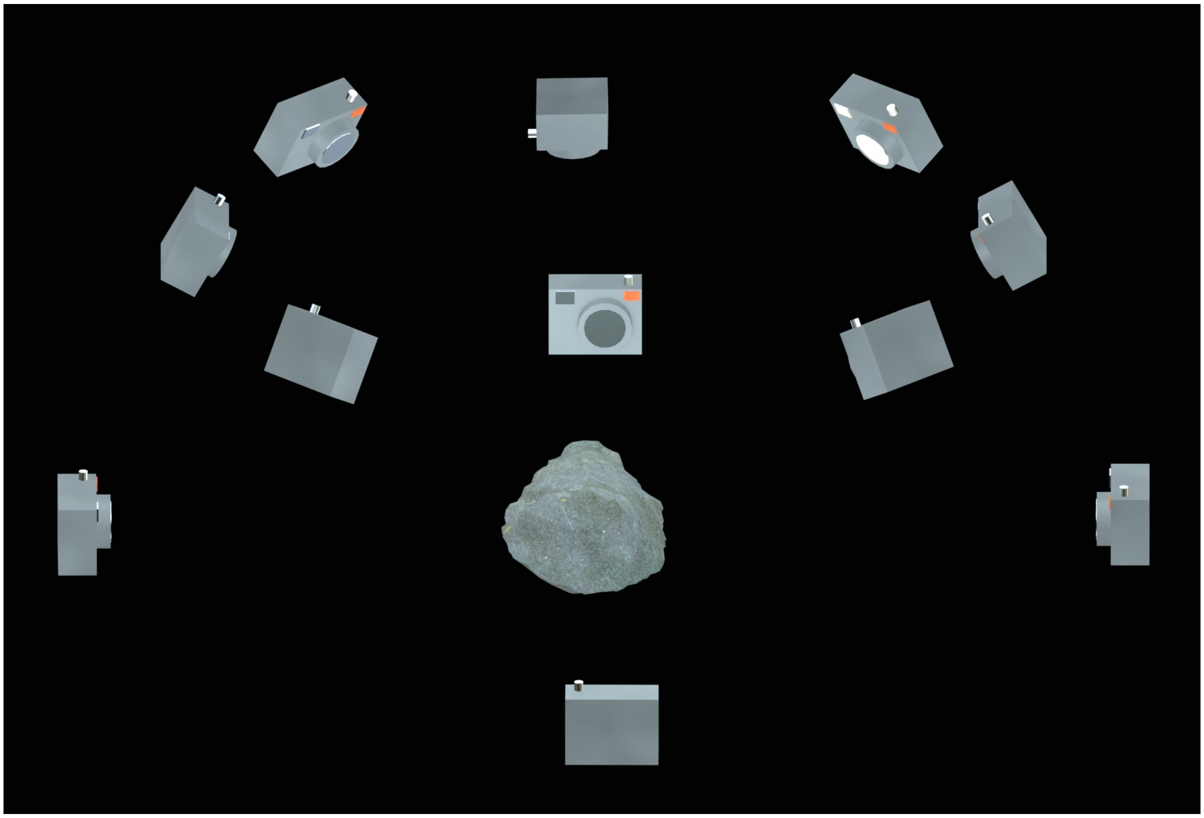
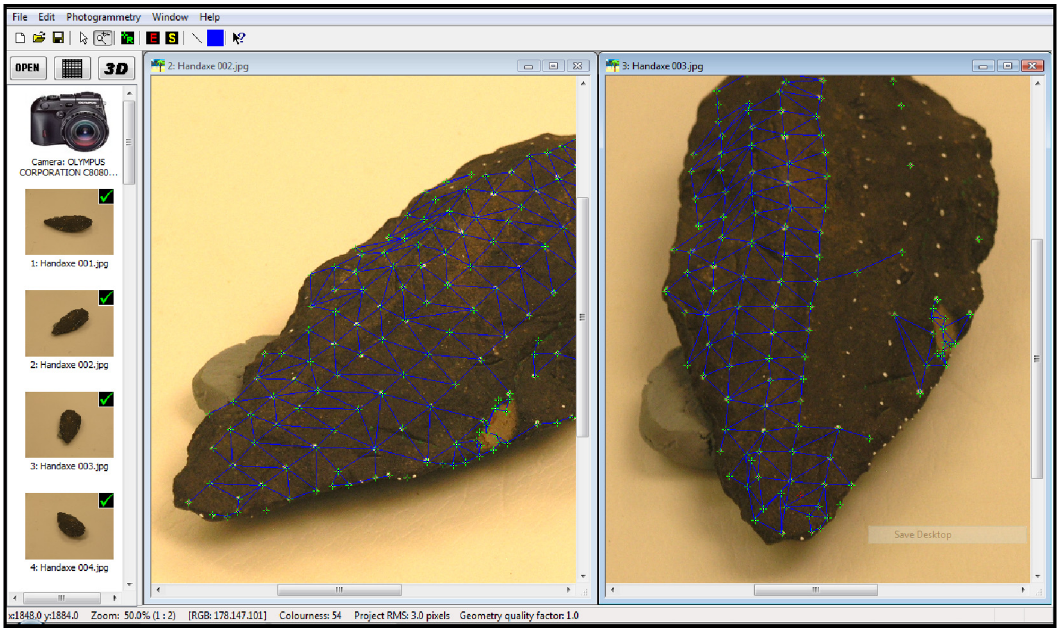


Figure 2. A virtual representation of the directions of image capture for one side of the handaxe. Cameras indicate the position and angle of the captured digital images.

level. How representative the model is of the real artifact depends on the features identified in the photogrammetric stages. Second, the greater the number of points identified on the artifact, the greater degree to which the model represents the actual artifact. While the overall form of a microblade core could be modelled using a few dozen points, the topography of the removal faces and platform, including individual flake scars, could only be replicated by identifying many more precisely chosen points. Increasing the number of modelled points not only enhances how



x:1848.0 y:1884.0 Zoom: 50.0% (1 : 2) [RGB: 178.147.101] Colourness: 54 Project RMS: 3.0 pixels Geometry quality factor: 1.0

Figure 3. Detail of iWitness *window illustrating point-to-point matching between two images of differing visual orientation.*

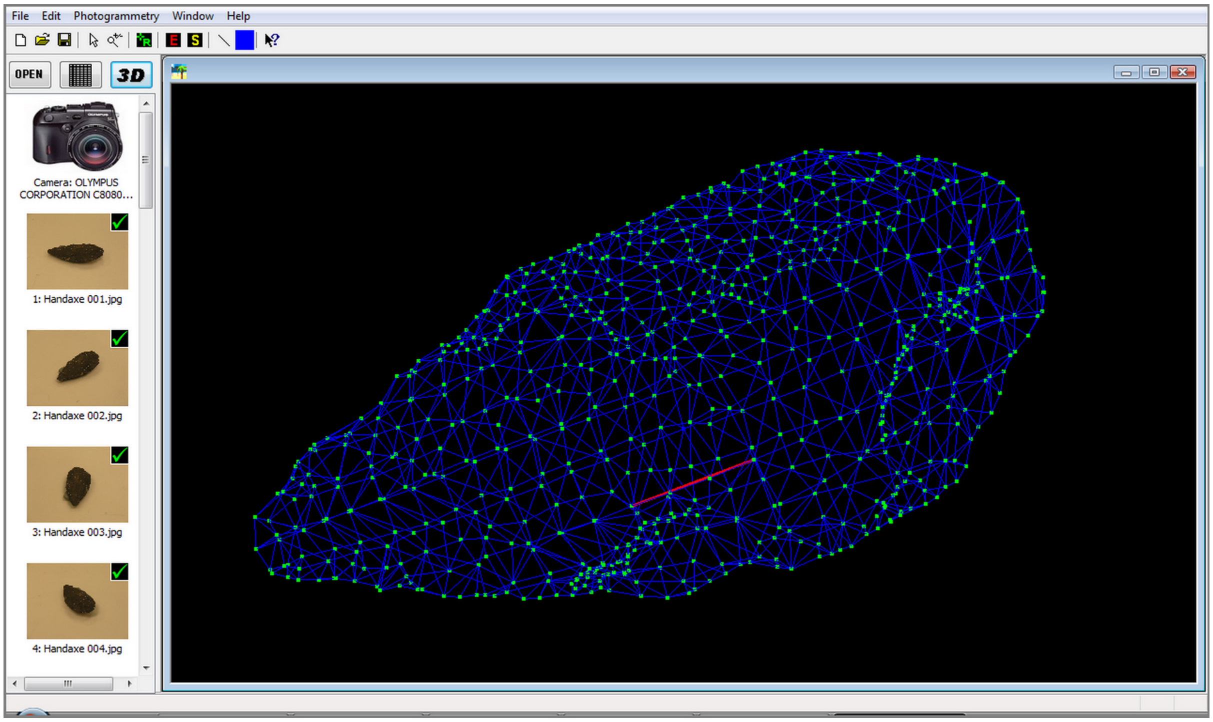


Figure 4. Handaxe replicated in point-cloud form with added triangular mesh surface construction.

representative it is, but also increases the time and effort required to identify, map, and link those same points. This is a subjective process and, consequently, one must decide what level of detail is required and choose the number of points to be used accordingly.

CASE STUDIES

HANDAXE RECONSTRUCTION

In 1961, construction began of the High Dam at Aswan in Egypt. The construction of the dam was to result in the permanent flooding of a great region of the Nubian frontier south of the proposed project region. Consequently, the United Nations Educational, Scientific, and Cultural Organization (UNESCO) called for the immediate salvage of those historic and prehistoric sites under threat of flooding in the region. Working under the name 'Yale University Prehistoric Expedition to Nubia' (YUPEN), a diverse group of researchers including, among others, Charles A. Reed of Yale University, Philip E.L. Smith from the National Museum of Canada, Maxine Kleindienst from the University of Toronto, and Robert Geigengack from the University of Pennsylvania surveyed the lower Nile River Valley over three field seasons between 1962 and 1965. Portions of the YUPEN collection are now housed at Yale University in New Haven, and the University of Toronto. From the latter collection, the authors selected an Acheulian handaxe recovered from the Dihmit region, south of Aswan, to serve as their initial test subject. The specimen is a standard marker for both the Paleolithic period and lithic studies in general and is therefore recognizable to researchers working in most geographic regions of the world.

The ferrocrete sandstone from which the handaxe was made has developed a fairly uniform dark brown patina. Thus, in preparation for the initial acquisition of artifact images, it was decided that points on the handaxe would be marked using water-based white gouache paint to facilitate easier point identification. Minute dots were painted onto the entire surface of handaxe in linear format and at regular intervals. Ultimately, treatment of this kind is not necessary and it was not applied to Sumner's Middle Paleolithic materials. In the vast majority of cases, the existing surficial patterning of an artifact is more than sufficient for point identification. Notable exceptions, however, include obsidian and quartz crystal, materials whose homogenous, high-luster, and translucent appearances make the accurate identification of surficial points difficult. Of course, there are many kinds of artifacts, especially those of rare or delicate nature, which could and should not be treated in this manner.

The artifact was positioned on a flat surface supported by a clay block. A standard laboratory desk lamp was used in conjunction with ambient fluorescent light to illuminate the specimen. A total of sixteen digital images of the handaxe were obtained using an Olympus C8080WZ Digital SLR camera. Images were taken at a uniform distance of two feet capturing both faces of the handaxe from normal and oblique angles as indicated in Figures 1 and 2. Once the first face was digitally recorded, the artifact was rotated on the clay stand to display the opposing face. The images were then downloaded onto the laboratory laptop and imported into the photogrammetry program.

The next step of the process was the most time intensive. Rectification of the images with one another, followed by manual triangular meshing of 3D point-clouds as seen in Figure 3, required approximately ten hours to complete. Several factors contributed to this. First, the use of gouache surface indicators allowed for the identification of over four hundred points, all of which had to be identified and matched on at least three, and often more, images. Second, these same points must then be connected to adjacent points to complete the wireframe mesh, an operation that is likewise slowed by the great number of surficial points. Third, and perhaps most significant, was the authors' unfamiliarity with the software, which became less problematic as work progressed. When Sumner applied this method to her research samples (described below), the average time of artifact reproduction—beginning with the photogrammatic rebuilding—was reduced from the handaxe case study time of ten hours to approximately five hours. Put another way, a good morning's or afternoon's work would supply the researcher with a digital replica of the required specimen.

It is also important to point out that the requirements of the researcher, specifically in terms of the level of surficial resolution desired, will dictate the time needed to replicate the specimen. If minute or otherwise highly-detailed characteristics of an object's surface are desired, a lengthier replication process is to be expected. On the other hand, if the overall morphology and general appearance of the specimen is of interest, processing time will be notably reduced. Also, one might not need to model the entire artifact. Significant time and effort can be saved by modelling only those portions of a specimen that are of interest or, alternatively, by modelling portions of interest in high-resolution and the rest in lower resolution. The researcher can decide on her/his priorities for a particular study, while knowing that the artifact can be modelled any number of times from the same set of images.

Once the photogrammetric stage was completed, the data file from *iWitness* was exported to *3DS* as a wireframe. Here, the virtual artifact is given a surface using the built-in 'skin' modifier. Errors in the construction of the spline wireframe become evident in the model as gaps in the surface skin (Figure 5). These are easily rectified by adding, adjusting, or removing segments as necessary. When finished, the model was given a surface texture and appearance resembling stone. Figure 6 shows the completed model alongside an image of the actual handaxe.

Overall, our handaxe model approximates the form of the actual artifact exceptionally well. Measurements of length, width, and thickness at various axes of cross-section, as well as the form of surficial features such as flake scars, revealed an astonishing low margin of error of approximately 0.1mm based on manual measurements with dial callipers. In all cases, the manual measurement was recorded first and served as a comparator for the more precise and reliable computer-based measurements. These results exceeded our initial expectations, specifically because our focus for this trial was evaluating the feasibility of the method. A follow-up study is currently in progress to more thoroughly evaluate the potential accuracy of our photogrammetric method for modelling a variety of cultural materials. Nevertheless, it is encouraging that a high degree of morphological accuracy can be obtained with such relative ease.

While we remain satisfied with the outcome of the handaxe model, the process has revealed a number of modifications that would improve our methodology. The first is the systematic identification of multiple points on prominent surficial features. Arrises, hinge scars, and other such features require several points, often situated on adjacent surfaces, to be accurately represented in digital models. This holds especially true for artifact edges that, if modelled with insufficient points along the intersecting surfaces, become unrealistically 'sharp' in their digital form. We see this problem in the handaxe model and have adjusted our method accordingly to avoid future problems. Similarly, the modelling process could benefit from multi-stage feature mapping where surface, edges, and surficial features are modelled separately and are then integrated using common datum points into a single model. Although more complicated and time intensive, this method would result in fewer errors during the framing process because extraneous points would not be present to confuse the user. Also, mounting artifacts on a rotating stand would allow for object reorientation while keeping the camera stationary and thus maintaining focal distance. Finally, it was noted that a systematic rule-set was needed to remove as much subjectivity from the point-connection process as possible. Such a process is currently in development.

REPRODUCTION OF MIDDLE PALEOLITHIC REFITTED CORES

The analysis of a sample of Middle Paleolithic (MP) refitted cores from the site of Taramsa Hill, Egypt, has benefited from the present methodological approach. The aim of this research is to track morphological characteristics of 29 reconstructed cores at various stages of reduction. The original refitting of these cores reflects the impressive work of Philip van Peer of the Katholieke Universiteit in Leuven, Belgium, who generously granted Sumner access to the collection and, more importantly, gave permission to deconstruct the refits in order to better understand the dynamic process of reduction. Analysis of this collection naturally required travel to Belgium from Canada to access the artifacts in question. Time constraints on visitation, however, proved problematic and did not allow for the detailed analyses required on location. Consequently, all 29 Taramsa cores were photographed by Sumner in Leuven, from which a sample of 10 cores were selected for the specific intention of three-dimensional replication. A series of high-resolution images were taken of the cores in varying stages of reduction. Upon return to Toronto, these images were used to reconstruct the surface of each of the 10 cores using *iWitness*. Following the same procedure as for the previous case study, excluding painted surface markers, digital replicas of the cores from Taramsa Hill were created in the University of Toronto lithics lab (Figure 7).

From three-dimensional models, a series of informative analyses can be conducted without physical access to

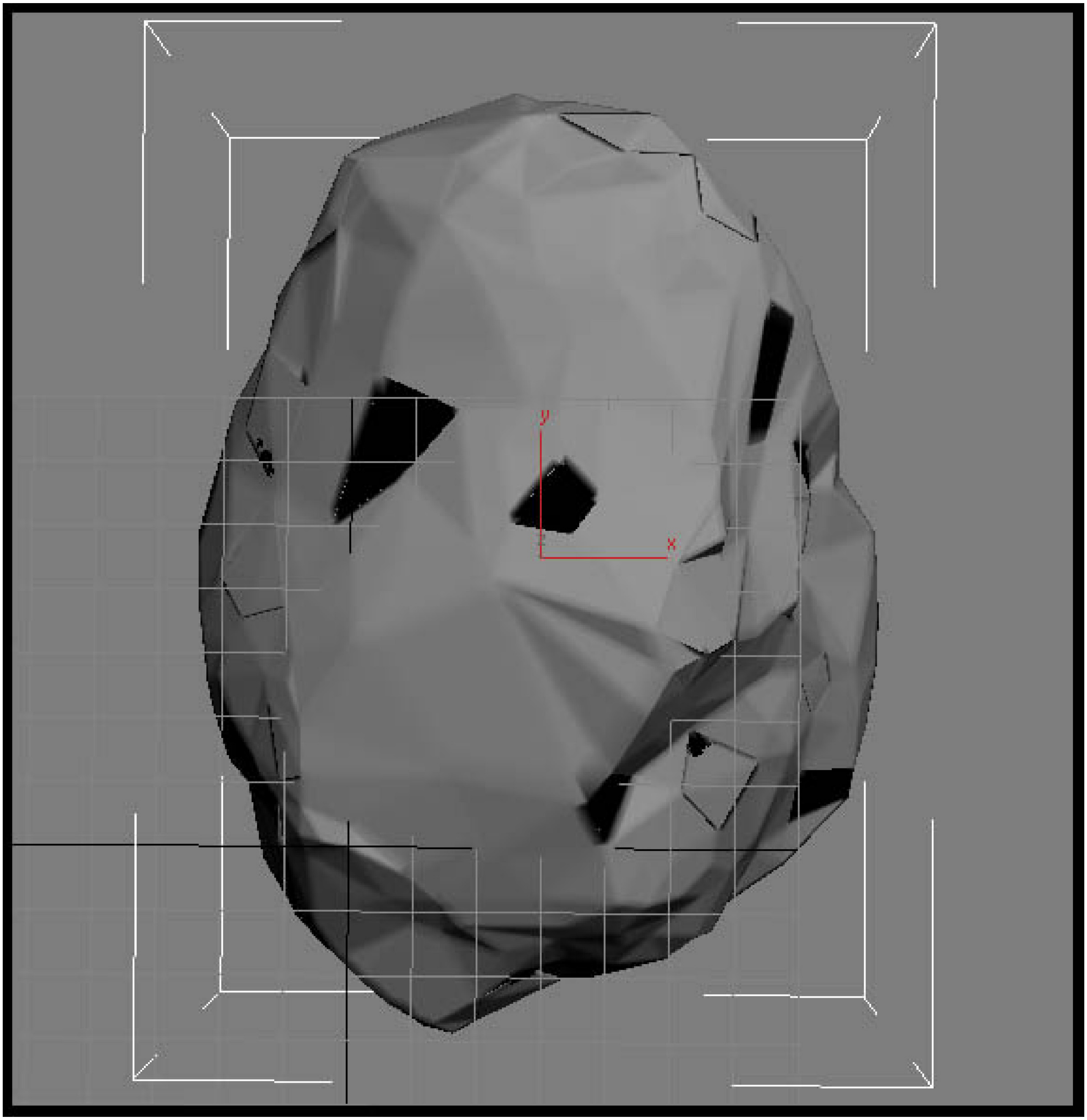
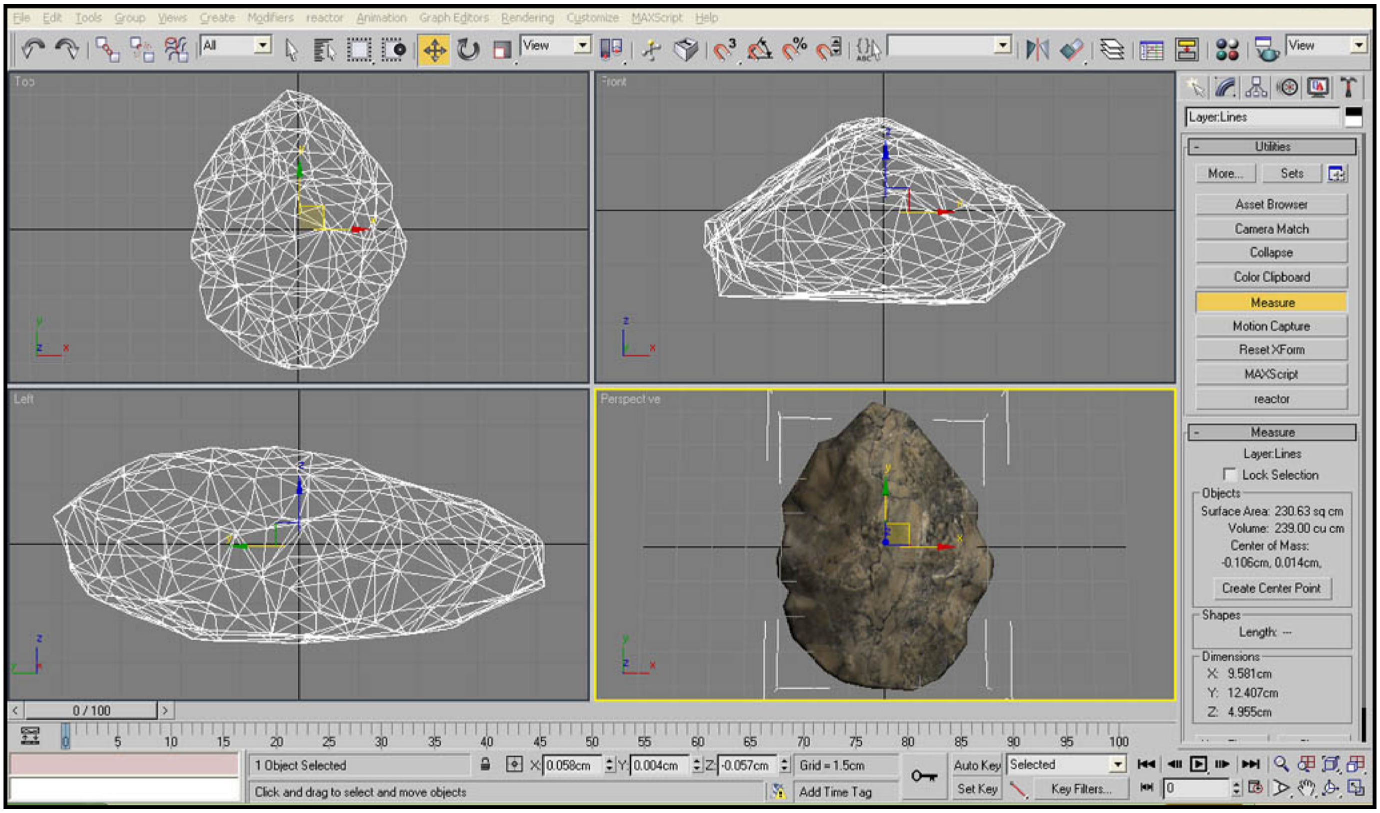


Figure 5. Incomplete three-dimensional reconstruction of a Taramsa core. Gaps in artifact surface are a result of incomplete wireframe construction in iWitness.

the artifacts themselves, several of which are difficult if not impossible to accomplish by traditional methods. One of the most pertinent analyses to Sumner' research is the calculation of surficial convexity, or the curvature of the core surface. Using the *3DS* program, one is able to section the replicated cores as needed; in this case, multiple cross-sections were taken from predetermined points along the long axis (Figure 8). In doing so, 'thin sections' of the cores are produced allowing for the measurement of upper surface convexity**.** Convexity is here measured as the slope of the arc that most closely approximates the superior core surface. Bulbous surfaces result in slopes approaching a value of one (spherical), whereas near-flat surfaces have slopes approaching zero. The cross-sections produced from the model make possible the calculation of a convexity index that can be used to compare upper surficial core convexity while controlling for variability in core size. Convexity is believed to be a significant feature of these cores because

Figure 6. Comparison of actual Dihmit handaxe (right) with 3DS replica (left).



Layer:Lines

Measure
Layer:Lines
☐ Lock Selection
Objects
Surface Area: 230.63 sq cm
Volume: 239.00 cu cm
Center of Mass:
-0.106cm, 0.014cm,
Shapes
Length: --
Dimensions
X: 9.581cm
Y: 12.407cm
Z: 4.955cm

1 Object Selected
X: 0.058cm Y: 0.004cm Z: -0.057cm
Grid = 1.5cm
Selected
Click and drag to select and move objects

Figure 7. Detail of 3DS *window showing successful replication of one surface of Taramsa core 28.10.*

this aspect of upper surface core morphology plays a central role in determining both the shape and number of products removed from the prepared surface. Generating artifact cross-sections on any axis, quickly and accurately, without physically damaging the artifact under study, is clearly of great value for morphological analyses.

In addition to the virtual dissection of the Taramsa cores, automatic metrical values of surface area, core volume. and center of mass were produced for export to an SPSS spreadsheet for further statistical analysis. An additional illustrative function of the *3DS* software is the facile production of customized video. One can produce simple or complex animations, such as model rotation, sectioning, or morphing. This is an invaluable tool for illustrating aspects of artifact morphology not easily conveyed by two-dimensional images alone.

On a practical level, the methodology used by Sumner provided the freedom to continue analysis of the sample in Canada. Research expenditures for residency in Belgium were significantly reduced. For researchers with limited research funds, the reduction in costs is an important consideration. At a procedural level, three weeks were required to reconstruct the sample of twelve cores in three stages, totalling thirty-six surfaces. The resulting models provided a range of essential morphological data. Because all information was contained on a notebook computer, the ability to access these data, at any time and in in any place, expedited the analysis. Additionally, having access to these digital models opens up the possibility for future exploitation of the same cores.

SIGNIFICANCE FOR PALEOLITHIC STUDIES

While the methodology presented here can be applied to many archaeological contexts, our concern here is how it can be profitably used to facilitate, expand, and further Paleolithic research. Speaking of three-dimensional models in general, the most significant benefits are these: 1) the ability to manipulate virtual artifacts in ways that would be destructive to real artifacts; 2) the facile calculation of complex metrics; and, 3) improved accessibility to artifact specimens. Beginning with artifact manipulation, it must first be said that Paleolithic artifacts, particularly those dating to the very earliest periods of the Lower Paleolithic, often are rare. Not surprisingly, destructive forms of analysis, such as sectioning, are simply not realistic options for researchers. Virtual models, on the other hand, are infinitely replicable and can be analysed in ways that would otherwise damage a real artifact. Sumner's analysis of the Taramsa cores exemplifies the utility of this application.

The second benefit of digital modelling is the ease with which one can perform the calculation of measurements that are difficult by traditional means. 3DS offers built-in tools that automatically calculate the volume, surface area, and center-of-mass of a model, the last two being notoriously difficult to determine even for objects with simplistic morphologies. Point-to-point measurements can be made anywhere on the model and the reliability of such measurements is assured. Also, CAD-based software packages can offer even more options for morphological analyses of virtual artifacts, expanding the possibilities for technologi-

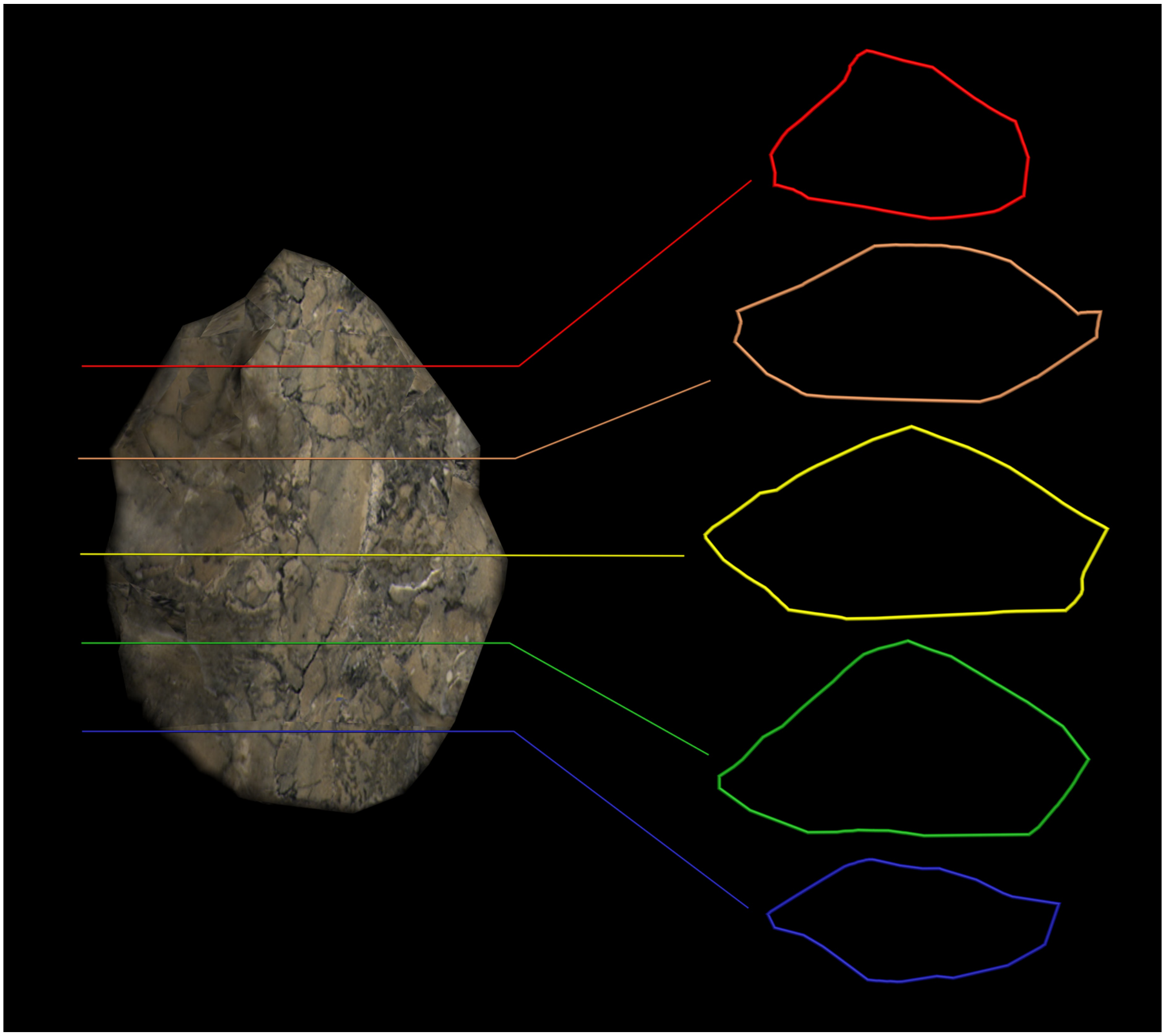


Figure 8. Five cross-sections of Taramsa core 28.10 taken at equidistant points along artifact length.

cally-based research while maintaining a high degree of accuracy and reliability.

The third benefit that three-dimensional modelling affords Paleolithic research, and arguably the most exciting one, is the opportunity for digital sharing of virtual artifacts and even entire assemblages. Paleolithic artifacts are housed in research institutions throughout the world. Due to governmental regulations and guidelines concerning the management and conservation of archaeological materials, the removal and transport of artifacts from the host country to a one's base of study can be difficult, costly, and time intensive. Researchers must occasionally rely on photographs and hand-drawn illustrations of specimens for future examination, media limited in how well they represent the actual object, and analytical versatility. The ideal situation, of course, would be to have unlimited access to collections stored anywhere. Digital modelling makes this possible. The establishment of databases such as proposed by Boehler et al.(2003), and the Internet-based Digital Archive Network for Anthropology (DANA) outlined by Clark et al. (2001) would provide the framework through which data could be distributed, openly or selectively, to the archaeological community via the internet. Alternatively, models and related data could be distributed from one researcher to another directly by request. Regardless of the form it takes, the widespread availability of digital artifact assemblages would represent an invaluable resource for Paleolithic researchers, both in terms of acquiring additional data and sharing cultural materials with those unable to access it firsthand. Furthermore, unique artifacts or those originating from the earliest stages of human prehistory are often in great demand, and thus access to these rare specimens can be restricted. The ability to digitally replicate these artifacts would provide more researchers with access to these exceptional finds. As three-dimensional modelling techniques become more commonplace in research institutions, the archaeological community can only benefit from the new sources of information that will emerge.

What role, then, does photogrammetry play in the development of a 'Virtual Paleolithic'? The photogrammetric approach described in this paper affords the above mentioned advantages as well as one other—the opportunity to create models without requiring direct access to the specimen. As yet, digital artifact libraries are practically non-existent. Until such a time that they are made widely available, researchers must begin building datasets that can be distributed and integrated into research programs. Yet, we are once again faced with the problem of geographic separation from cultural materials of research interest. Photogrammetry bridges this divide by making it possible to construct virtual artifacts 'at home' using only digital images. This is perhaps the most significant feature of the approach; that a colleague in a distant location, perhaps even halfway around the world, can request digital images of a unique artifact or paleoanthropological specimen in the morning and by the end of day the recipient of the images can be 'rebuilding' the object for virtual analysis or simple observation. The relatively low cost, portability, and overall ubiquity of digital cameras ensures that the requisite images can be easily obtained. Consequently, photogrammetry represents a convenient, cost-effective alternative to digital laser scanners for researchers interested in exploring three-dimensional artifact modelling and analysis. Nevertheless, the authors wish to emphasize that the methodology reviewed here is best suited for the reproduction of unique or otherwise singular finds and not for whole collections. Large scale replication of assemblages numbering in the hundreds or more would best be accomplished with digital scanning equipment, which provides superior resolution and reduced procedural subjectivity in far less time per specimen. Photogrammetry is not a replacement for 3D scanners, but rather a robust tool that can be employed in diverse contexts, and, in particular, those where use of the latter is not feasible.

CONCLUSION

The significance of photogrammetric modelling to aspects of Paleolithic research is reviewed in this paper. The initial case study modelling the Acheulian handaxe demonstrated the ease with which an artifact can be replicated from digital images while maintaining a high level of morphological accuracy, in this case to within the thickness of a sheet of paper. This method was then applied to a sample of Middle Palaeolithic refitted cores from Taramsa Hill, Egypt, where the versatility of the modelling process allowed for convenient off-site model production leading to timely analysis of the sample. Considering the distribution of Paleolithic assemblages worldwide and the barriers to studying those collections, having access to virtual artifacts is an attractive prospect. Paleolithic researchers can benefit from the ability to share their collections with other scholars who can then exploit them as needed. This, in effect, increases the mobility of artifacts that would otherwise be inaccessible to the majority of the research community. Furthermore, one can expand one's research samples via the inclusion of foreign specimens that complement particular research goals. Once acquired, three-dimensional models allow for expanded and highly detailed technological and morphological analyses.

The current interest in computer modelling applications for archaeological analysis has led to a surge of investigations into the most effective systems for reproducing prehistoric sites and artifacts. It has become apparent that no one methodology is suitable for all contexts. Consequently, researchers must choose the approach that best suits their financial resources, time limitations, and research requirements. Following the results of our preliminary modelling assays, it is clear that photogrammetric modelling is a viable alternative to laser scanning technologies for many research programs. Regardless of the specific methods researchers employ, three-dimensional modelling has the potential to open valuable avenues of information sharing and collaboration within the paleoarchaeological and paleoanthropological communities.

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