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Author(s): Harriet F. (Rae) Beaubien and Basiliki Vicky Karas
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3D SCANNING OF DEER STONES ON THE MONGOLIAN STEPPE

Harriet F. (Rae) Beaubien and Basiliki Vicky Karas

Abstract

The Smithsonian’s Museum Conservation Institute has been exploring the use of 3D imaging technology in conservation, including field applications. As part of a collaborative Mongolian-Smithsonian archaeological project in northern Mongolia, MCI conservators tested this technology in the documentation of Bronze Age carved stone monuments during the 2005 and 2006 field seasons. This paper discusses our experience with two different types of portable 3D scanners (laser and structured-light), and the conservation uses of the data.

1. Introduction

Deer stones have been a significant focus of research for the Joint Mongolian-Smithsonian Deer Stone Project (DSP), a multi-disciplinary collaboration working in northern Mongolia since 2001 [1]. Hundreds of these carved stone monuments, dating to approximately 3,000 years BP, are distributed across Mongolia’s vast steppe (Figs.1, 2).

Figure 1. Ulaan Tolgoi site, showing deer stones and associated burial features (Photo by P.T. DePriest 2004).
They are considered to be among the most important archaeological treasures of Central Asia, yet very little is understood about their age, stylistic development, function and meaning within the cultural contexts that produced them. This is due in part to their geographic isolation, which has hampered systematic documentation and archaeological investigation. They are additionally endangered by unprotected exposure to harsh environmental conditions, with on-going deterioration from weathering, biological effects and, increasingly, human impact. These factors give high priority to research and documentation efforts, which the DSP has incorporated into its program of investigations in the northernmost province of Hovsgol aimag.

Documentation activities, carried out by conservators from the Smithsonian’s Museum Conservation Institute (MCI) since 2005, include the use of 3D scanning technology [2]. The technology provides an effective, rapid, accurate and non-contact means of capturing accurate and detailed topographic information in digital format. This paper presents an overview of 3D scanning during the 2005 and 2006 field seasons of the Deer Stone Project, using two different portable scanning methods, and the anticipated conservation uses of the data.

2. Deer stone documentation

Deer stones – often surrounded with ritually buried deposits of horse crania, cervical vertebrae and hooves, and associated with larger stone burial complexes called khirigsuur – are thought to be commemorative monuments of leaders of nomadic peoples who inhabited the steppe during the Bronze Age-Early Iron Age. They are typically ornamented in low-relief carving with a zone of ornately antlered creatures, framed by ring elements and belt-like bands hung with various
tools.

Of the estimated 700 found in the steppe regions of Central Asia, over 550 are in Mongolia alone. No comprehensive inventory of these monuments currently exists, although a publication by Volkov (2002), a Russian researcher working Mongolia in the decades prior to its independence in 1992, provides a useful foundation and is one of the few accessible resources. He catalogued approximately 400 deer stones from 82 sites, and illustrated a small percentage of these with sketch drawings. In general, documentation of all but a few of Mongolia’s deer stones is incomplete, and generally limited to selected photographic views and non-technical drawings.

An early attempt to document a deer stone in three dimensions was carried out by the DSP in 2002 using a conventional mold-making process, with a stone famous for its unique incorporation of a human face in its iconography (Ushkiin Uver DS #14). It was robust enough to withstand applications of liquid soap, silicone rubber and polyurethane foam mold layers, in a process that took several days, carried out by skilled model-makers and with imported materials. The mold was brought back to the Smithsonian, and several casts were made at the Office of Exhibits Central, one of which was later returned to the National Museum of Mongolian History in Ulaanbaatar for display (Fitzhugh 2002, Fitzhugh 2003a:31). The limitations of this molding and casting approach for documenting deer stones, many of which have weathered and deteriorating surfaces, encouraged MCI to propose the use of 3D scanning technology as part of the documentation effort, which would also include systematic photography, descriptive information and condition records.

3. Laser scanning - 2005 Field Season

The 2005 field season of the Deer Stone Project was our first opportunity to test the feasibility of using 3D scanning as a field documentation tool, based on preliminary work carried out by Karas (then-MCI conservation fellow) (Karas 2006). The scan team consisted of the authors, as well as Carolyn P. Thome (model-maker, Smithsonian’s Office of Exhibits Central), who was involved in the molding and casting of Ushkiin Uver DS #14 three years earlier. During a three-week period in the field (June-July), the team conducted tests on twelve deer stones at six sites in Hovsgol aimag, as described in the following sections.

3.1. Scanning equipment

A handheld Polhemus FastSCAN Cobra laser scanning system was used by the MCI scan team in 2005. Its key components are the wand (range finder), the transmitter, the reference receiver (optional) and the processing unit, all safely transported in a customized Pelican 1610 case (Fig.3).
The Polhemus system software was run on a Hewlett-Packard Pentium IV laptop computer. The computer and scanner were powered in the field by a portable Honda EU1000i generator developed specifically for use with precision equipment.

3.2. Scanning process (general)

A 3D data file for the object is constructed from a series of “sweeps” of the wand, which is moved in a controlled motion approximately 10-15 cm above an object’s surface (Fig.4).

The wand projects laser light in a thin line (<10 cm in length), at a wavelength of 670 nm, through a centrally-mounted laser line generator. The wand operates at a scanning rate of 50 lines per second and with a resolution of 0.5 mm (Polhemus 2001; Polhemus 2004). A profile of the object’s surface, consisting of thousands of 3D coordinate points, is created at every intersection of the laser line with the surface. The miniature camera in the wand simultaneously records the changes in surface shape, based on varying angles of reflectance of each profile, and each point is individually located in 3D space through triangulation (Fig.5).
The triangulation process relies on the fixed position of both laser-line generator and camera, and the transmitter which generates magnetic fields in three directions. The amplitude of these fields locates the position and orientation of a receiver mounted in the wand. One component must maintain a fixed (unchanging) relationship with the scan subject, and two options can be followed. The first uses the transmitter as the fixed datum, which means both it and the object must remain immobile during scanning. In this case, the computer locates each profile relative to the transmitter. The second option (used in the Mongolia project) uses a small reference receiver, which is attached to the object surface to serve as the fixed datum. In this configuration, the computer locates each profile relative to the reference receiver rather than the transmitter, which can be moved or carried during scanning; the object with its attached receiver can also be moved as needed. During scanning, the area of the attached reference receiver is avoided until the end, when a final procedure is carried out: the transmitter is anchored and temporarily established as the fixed datum, the reference receiver is removed, and the final missing area is scanned.

With either configuration, scanning must be carried out in a single episode. During scanning, the digitized 3D information conveyed by all these components is calculated by the processing unit and the computer, and is simultaneously mapped by the system software in graphic form; this is displayed on the computer screen, and serves to guide the progress of scanning. The “raw data” can be displayed in point-cloud, wire-frame, or solid graphic formats. Note that color information is not collected by this system.

3.3. Field procedures

The portability and compactness of the laser scanning system were ideal for use in the field, but several features posed challenges in creating a suitable scanning environment for each deer stone: sensitivity to direct sunlight, which interferes with the data capture; poor performance in cold environments; and inability to be used in the vicinity of metal objects, given the system’s use of magnetic field triangulation and resulting distortion in spatial data. To create adequate conditions for scanning during the day, temporary tent-like shelters were built over the deer stones using wooden poles (including 5-meter lengths borrowed from nearby animal corrals) which were draped with medium-weight canvas (40 m, sewn into a 10 m x 6 m panel),
supplemented inside with light-weight black fabric (Fig.6).

![Figure 6. Shelter set-up used for laser scanning, shown with Ulaan Tolgoi DS #5 (Photo by H.F. Beaubien, 3 July 2005).](image)

The scanning configuration included use of the reference receiver, attached to the deer stones using lightly applied adhesive tape. One person scanned with the wand, another provided guidance based on the computer display, and another adjusted localized shading.

In 2005, a total of 12 deer stones were scanned, 9 of which resulted in complete data files [3]. One of the 3 incomplete data files was that of Ulaan Tolgoi DS #2, the tallest known deer stone at 3.8 m (visible in Fig.1). Its great height exposed a shortcoming of the Polhemus system. The reliance on a fixed datum point and functional range limits between the system components meant that objects over a certain size could not be scanned as a single unit; in this case, files for upper and lower halves were generated. The data quality was also inferior, because of the difficulty of shading the stone during scanning. For the successfully scanned deer stones, an average of 2 to 3 hours each was required for setting up the shade shelter and scanning; two could be completed in a day’s time.

### 3.4. Data processing

The raw data files collected for each scanned stone ranged in size between 23 and 96 MB, and were easily stored on the laptop computer. It is typical that scan data files are flawed by noise (areas of light interference, overlapping data) as well as areas missed in scanning (Fig.7).

These are cleaned up in a series of post-processing steps that require considerable time. The Polhemus data in particular contain noise derived from an inherent weakness in the working properties of the hand-held laser scanner and system software.
Raw data from each of the deer stones were processed by Karas in two steps, which required a total of approximately 12 hours per deer stone data file. The first step used the Polhemus system software, in which the sweeps were aligned (or registered) and merged to produce a “basic surface.” The system software could be used to cut out data from adjacent materials (grass, ground surface) as well as extraneous noise resulting from light leakage, but most of this work was impractical to do in the field. Any further editing also required more sophisticated software, so was done later at MCI. Using the system software, the basic surface files were saved as stereo tessellation language files (STL), a commonly used format for non-color data, and imported into other 3D graphic software for the second step of editing.

The 3D graphic software principally used for editing was Rapidform XOS (INUS Technologies Inc.); PolyWorks (InnovMetric Software Inc.) was also used in processing one of the files. The most problematic noise was imperfect surface data that appeared as numerous irregular spikes in the polygonal mesh. These were extremely difficult to remove without losing good data in the surrounding mesh. As a result, the spikes were mechanically reduced as much as possible but not completely removed, in order to minimize data loss, and thus are still visible when viewing STL files from all laser scanned deer stones.

Filling voids in the data was also carried out in this software, which allows the operator to select the particular holes to fill and creates a fill by extrapolating curvature from the data mesh surrounding the hole. This program displays the fills as a uniform mesh (in mesh view), or as smooth patches for larger fills (in solid view), so that fills are always detectable. The fully processed data files are saved as new STL format files, for archival purposes and use in other applications (Fig.8).
4. Structured light scanning – 2006 Field Season

The promising results from scanning in 2005 encouraged MCI to acquire a different type of scanning system that was specifically developed for cultural heritage applications, and to test its use in the field. The 2006 scan team consisted of the authors and Leslie G. Weber (then-MCI conservation fellow), along with an archaeological assistant, Songuulkhuu Namjil. During a three-week period in the field (June), the team scanned 15 deer stones and three fragments at two sites, as described below.

4.1 Scanning equipment

A Breuckmann triTos (GmbH) structured light system was used for scanning in 2006. Its components include the tripod-mounted sensor bar (in this case 30 cm long) with projector and camera, and the controller, safely transported within a custom-made hard case (Fig.9).

The structured light projection is calibrated using optical calibration plates, housed separately. The camera lenses are interchangeable to give varying fields of view; in this case, 675 mm lenses were used, which allowed a field of view for each “patch” of 67 cm on the diagonal and a working distance of 1.085 m. The triTos system software was run on a Hewlett-Packard Pentium IV laptop computer. The computer and scanner were powered in the field by the Honda generator used in 2005 and stored in the interim in Ulaanbaatar.
4.2 Scanning process (general)

A 3D file for the object is constructed from “patches” of data that are stitched together during the scanning process. For each patch, the proper working distance is established by aligning two laser dots on the object’s surface, and then a series of organized patterns of structured light is projected in quick succession (Fig. 10).

The patterns are simultaneously photographed using a digital camera that is aligned with the projector. The photographic images capture the edge distortion of the projected light pattern as it strikes the object, as well as color information. The system software processes the distortion and color information to generate 3D point cloud data. Because the point cloud’s (XYZ) range and (RGB) color values are recorded together, the color information is registered exactly with its corresponding 3D point. After the light sequence is completed, the patch of new data is displayed graphically on the computer screen; it can be added to the previously acquired data by aligning several overlapping surface feature details. The data file can be temporarily closed and re-opened, which allows the scanning process to be carried out in more than one phase if necessary.

The triTos system has a triangulation angle of 20 degrees, which allows for fewer scans and
better data capture on objects with complex geometry, e.g., areas of high relief, although the tripod mounting can also inhibit access to some surfaces. Even with the lowest resolution lens, the resolution is 15-20 microns.

4.3. Field procedures

The structured light scanning system is somewhat sensitive to light conditions, which can affect contrast in the light patterns projected onto the object. As in 2005, day-time scanning required that temporary shade shelters be built over the deer stones, but these also needed to accommodate the 1.085 m working distance between the tripod-mounted camera and surfaces to be scanned. We modified our earlier shelter design by using traditional ger (yurt) walls to form a spacious rigid enclosure, in conjunction with a superstructure of wooden poles and canvas to create a relatively light-tight tent-like structure (Fig. 11).

Figure 11. Shelter set-up used for day-time structured light scanning, shown with Ushkiin Uver DS #3 (Photo by H.F. Beaubien, 15 June 2006).

The Breuckmann scanner did not have the Polhemus’ temperature sensitivity, so we were also able to scan at night, making a shelter unnecessary (Fig. 12).

Figure 12. Scanning set-up at night, shown with Ushkiin Uver DS #2 at night (Photo by B.V. Karas, 17 June 2006).
During scanning, one person operated the computer, another handled the tripod, and another assisted with shading and the tripod.

In 2006, 15 deer stones (one in three parts) and three additional fragments were successfully scanned, including Ulaan Tolgoi DS #2, which had posed problems in 2005 [4]. Night scanning proved to be the most effective arrangement, unrestricted by the shelter and providing ideal light-contrast conditions to produce excellent data. Because of its more cumbersome tripod mounting, however, scanning with the Breuckmann required more time than with the Polhemus, averaging at least 5 hours per stone.

4.4. Data processing

The raw data files from structured light scanning are very large, but can be stored on the laptop computer. For example, the largest deer stone (Ulaan Tolgoi DS #2) produced a 4.34 GB file, and after processing a 366 MB STL file. The data files are generally of excellent quality and relatively unflawed. The minimal noise arises from overlaps and alignment during scanning, and is easily filtered out during processing. Given logistical constraints in the field and computer memory requirements, however, this phase took place at MCI. The files were processed by Karas in two steps, requiring a total of approximately 6 hours per deer stone data file.

In the first step, the triTos system software (Optocat 2006) was used to convert the raw data files into STL and PLY files. The PLY format, in particular, is designed to store 3D data with a variety of properties, such as color information, surface normals and texture coordinates; these features allow the front and back side of the surface data’s polygonal mesh to have different properties. These were exported to Rapidform (XOS or 2006) 3D graphic software, used in the second step for all further processing. This included alignment, merging and filling holes (the latter as described in the Laser Scanning section above). The fully processed data files were saved as new STL and PLY format files, for archival purposes and use in other applications (Figs. 13,14).

Figure 13. Ushkiin Uver DS #2: computer screen view of the 3D digital file processed from structured light scanning, shown in STL format during editing in Rapidform (Photo by B.V. Karas, 2007).
While color capture is considered a desirable feature of this scanning system, in practice accurate color information (acquired by the digital camera) requires stringently consistent lighting conditions. These are not possible to achieve in a field situation, and as a result our PLY files have a distracting patchwork appearance from subtle variations in lighting as each data patch was acquired. Note that the topographic information, determined by edge distortion of the projected light patterns, is not affected by these variations, as seen in the STL files.

5. 3D Results and data applications

Field scanning in 2005 and 2006 produced complete 3D digital files for 24 deer stones and 3 additional fragments from the Hovsgol aimag sites of Evdt Valley 1, Ulaan Tolgoi, Erkhel East 1, Erkhel North 1 and Ushkiin Uver [2, 3]. The processed STL files, which are viewed using downloadable Free Viewer versions of the 3D graphic software, provide an often clearer view of decorative and technical features than photographs, and can serve as the basis for accurate drawings and other graphic products, as the example for Ushkiin Uver DS#14 produced at MCI by Melvin J. Wachowiak (2007), seen in Fig.15.
Figure 15. Ushkiin Uver DS #14: computer screen views of the four sides, taken from the 3D digital file (STL format) processed from structured light scanning. The roll-out illustration with vector overlays of images was created using Adobe Photoshop and Illustrator (Photo by M.J. Wachowiak/B.V. Karas, 2007).

Figure 16. Ulaan Tolgoi DS #5: computer screen view of the 3D digital file (STL format), with height calculations in Rapidform (Photo by B.V. Karas, 2007).

Metrological tools, which allow precise measurements to be taken between any set of points in the data file, are providing accurate dimensional information (Fig.16).

Contour lines allow data slices to be made for cross-sectional measurements, and to define baseline planes for use with color mapping or digital elevation tools. These tools could potentially be
used to monitor surface changes, such as erosion (Fig.17).

Thus far, MCI has tested several techniques of 3D model production using the STL files, with the assistance of the Smithsonian’s Office of Exhibits Central (OEC) and other commercial providers. These include computer numerical controlled (CNC) milling, where the data are used to guide the cutting tools, and rapid prototyping (also called 3D printing), where thin layers of casting resin are selectively cured in areas corresponding to data slices in the STL file (Figs.18,19).

Figure 17. Ushkiin Uver DS #14: computer screen view of the 3D digital file, color mapped in Polyworks (Photo by Steve Hand, 2006).

Figure 18. CNC milled model of Ulaan Tolgoi DS #5, produced in polyurethane at 25% scale from the 3D digital data, by the Smithsonian’s Office of Exhibits Central (Photo by C. Hollshwander, 2006).
Models (positives) can be manufactured at any scale and in a range of media; molds (negatives) can also be made from the STL file for conventional production of casts.

6. Conclusion

In summary, scanning offers a rapid, accurate and non-contact method of capturing 3-dimensional information with many applications in conservation, including in the field. The scan files can be graphically displayed in a number of ways to provide detailed iconographic, metrological and technical information for scholarly study. They can be used to record and monitor condition on a fine scale, and to carry out virtual reconstruction and compensation of loss. Models or replicas produced from the scan files offer greater accessibility for museums and research endeavors, and can potentially be used as in situ surrogates for severely threatened originals that can be removed to a suitable, protective and secure environment.

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Endnotes

1. The team, under the direction of Dr. William W. Fitzhugh (Arctic Studies Center, National Museum of Natural History), includes Smithsonian specialists from the Anthropology, Botany and Exhibits departments of the National Museum of Natural History, the Office of Exhibits Central (OEC), and the Museum Conservation Institute (MCI). Mongolian counterparts are from the National Museum of Mongolian History and the Mongolian Academy of Sciences, including the Institutes of Archaeology and of History, with the support also of the American Center for Mongolian Studies in Ulaanbaatar. For an overview of the DSP and archaeological site reports for each season, see Bayarsaikhan et al. 2005; Fitzhugh 2002; Fitzhugh 2003a; Fitzhugh 2003b; Fitzhugh 2004a; Fitzhugh 2004b; Fitzhugh 2004c; Fitzhugh 2005a; Fitzhugh 2005b; Fitzhugh et al. 2005; Fitzhugh 2006; Fitzhugh 2007; Neighbors 2005; Ochirkhuiag and Baiarsaikhan 2004. For regional survey reports, see Frohlich et al. 2004; Frohlich et al. 2005; Frohlich and Bazarsad 2006; Frohlich and Tsendsuren 2007; Wallace and Frohlich 2005.

2. MCI’s field documentation activities in 2005 and 2006 are reported in Beaubien 2006; Beaubien and Karas 2006a; Beaubien and Karas 2006b; Beaubien et al. 2007a; Beaubien et al. 2007b; Karas and Beaubien 2007; Karas et al. forthcoming

3. Complete 3D data files were produced for the following: Ulaan Tolgoi (Erkhel Lake) DS #s 1, 3, 4 and 5 (MCI 6085, see Karas 2007d); Erkhel East 1 DS #s 1 and 2 (MCI 6086, see Karas 2007b); Erkhel North 1 DS #s 1 and 2 (MCI 6087, see Karas 2007c); Evdt Valley 1 DS #1 (MCI 6088, see Karas 2007a). Incomplete 3D data files were produced for the following: Ushkiin Uver DS #1, Tsatstain Khoshun DS #1; Ulaan Tolgoi DS #2. Data files are archived at MCI, under project #s, as noted.

4. Complete 3D data files were produced for the following: Ushkiin Uver DS #1-#14 plus 3 fragments (MCI 6084 on-going, and MCI 6089, see Wachowiak 2007); Ulaan Tolgoi DS #2 (MCI 6085, see Karas 2007d). Data files are archived at MCI, under project #s as noted.

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**Authors’ Addresses**

Harriet F. (Rae) Beaubien, Museum Conservation Institute, Smithsonian Institution / Museum Support Center, 4210 Silver Hill Road, Suitland, Maryland 20746-2863, (301) 238-1235 (beaubienh@si.edu).

Basiliki Vicky Karas, Museum Conservation Institution, Smithsonian Institution / Museum Support Center, 4210 Silver Hill Road, Suitland, Maryland 20746-2863, (301)238-1221 (karasb@si.edu ).