3D Modeling for Analysis and Archiving of Ceramic Vessel Morphology: A Case Study from the American Southwest

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Introduction

Archaeological analysis of ancient artefact morphology, such as pottery, and the technological traditions that produced these has often been limited to 2D drawings, photographs, and manual measurements, because these were the only available means of recording these 3D artifacts. Early applications of geometric modeling and classification for archaeological ceramics (Birkhoff 1933, Shepard 1976) recognized the potential of such research, but were hampered by manual 2D recording methods.

However, recent advances in 3D digitization and computer-aided graphic design (CAGD) are now facilitating the capture and study of three-dimensional aspects of pottery and other artifacts. The 3D scans provide an accurate archive of these complex vessel shapes and the subtleties of each individual object (Fig. 1). With specially developed software, it is now possible to quantitatively measure and analyze attributes that are relevant to studies of standardization in craft production, such as vessel curvature, area, volume, and symmetry.

Figure 1. High-resolution 3D digital scan of Horned Toad effigy vessel (Roosevelt Platform Mound Study, this vessel was repatriated in 1999 in accordance with NAGPRA).

In this study, interdisciplinary research applies recent theoretical and technological advances in 3D scanning and computer-aided graphic design (CAGD) (3DK) to such morphological research problems and develops quantitative 2D and 3D measurements including vessel symmetry. Results of two case studies are presented by examining variability and symmetry among Salado pottery from central Arizona and Casas Grandes pottery from northern Chihuahua, Mexico, that date from the Classic period (AD 1280-1450). Implications for further developments of this innovative research approach are discussed.

The development of web-based digital libraries (Rowe 2002) of 3D artefact models (i.e., searchable, online databases) will allow these collections to be studied even when the artifacts are no longer available (i.e., when artifacts are repatriated or returned to native peoples or governments; sometimes grave goods are reburied with associated skeletal remains (cf. NAGPRA; UNESCO)).

An additional benefit is that artefacts from similar sites and contexts that are curated at various distant facilities may be studied together within the web-based digital environment and can be reached by wide audiences of researchers and the interested public.

Pottery Specialization in the American Southwest

The Salado phenomenon was marked by the production of Salado polychrome pottery and the building of platform mounds with aggregated communities (Rice 1998, Dean 2000) as it spread across the Sonoran Desert of the American Southwest and northern Mexico during the Classic period (AD 1280 - 1450). Salado pottery was traded over extensive areas of the greater Southwest (Crown 1994), including the important trade center of Casas Grandes, Chihuahua, Mexico (Ravesloot 1988).

Prehistoric potters of this region used hand-building methods to make a large variety of utilitarian, corrugated, and decorated pottery; the potter's wheel was not introduced in this area until after the arrival of Spanish explorers and settlers in the late 16th century. Native potters often used either a shallow plate, or the base of an inverted jar, as a mold for the base of a pot, then built up the sides and rim using combinations of either coil-and-scrape or paddle-and-anvil techniques. The pot was rotated throughout the production process; however, with these hand-built techniques, the quality and symmetry of the resultant vessel was largely dependent upon the skill of the craftsperson.

The differentiation of labor and the presence of craft specialists are markers of developing social complexity, and thus are pivotal to understanding the nature of prehistoric social and economic organization (Rice 1987, Stark 1995). Quantified assessments of potters' skill levels will aid studies of the development of craft specialization, part-time household crafts or full-time specialists with workshops producing uniform, standardized products (Simon 1994, 1998). Mathematical definition of characteristic points, accurate measurements, and 3D modeling are essential to shape classification of pottery collections and assessments of productive standardization.

In this initial study, we apply principles of geometric modeling and CAGD to quantify and compare symmetry of prehistoric pottery from Salado sites in the Tonto Basin of central Arizona and from the large trade center of Casas Grandes, Chihuahua, Mexico. Although these initial studies sample a limited number of vessels, the results indicate the utility of this analysis for wider evaluations of potters' skill and specialized production of these vessels.

Methods for 3D Digitization, Archiving, and Analysis

The *3DKnowledge* (3DK) project (http://3DK.asu.edu) is being conducted by an interdisciplinary team at Arizona State University involving researchers from archaeology, physical anthropology, biology, computer science, and industrial engineering, united by the common goal of creating and analyzing accurate three-dimensional digital models of both surface and volume data.

Current interdisciplinary research is applying recent theoretical and technological advances in 3D scanning and geometric modeling (CAGD) to such morphological research problems and developing quantitative 2D and 3D measurements, including symmetry based on 3D surface data (Farin 2001a, b). We are employing recent technology to enable capturing, archiving, and analyzing accurate, detailed 3D geometric models of these artifacts (Schurmans *et al.* 2002; Simon *et al.* 2002).

Custom-written software (the Ceramic Analysis Program developed by the PRISM team) is used to obtain attributes and measurements of interest to discipline specialists (Bae 1999, Farin 2002b). Many of these measures have wide applicability, as demonstrated by the pilot projects, which include bones, lithic tools, and pottery among others.

The 3D Scanning Process We first give a brief outline of the 3D digitization process. The ceramic vessels were laser-scanned with a Cyberware 3030 Laser Scanner (with RGB color) to capture the three-dimensional geometry (Fig. 1) of the vessel surface. For restricted vessels, such as jars, only the exterior surface is scanned, but in the case of unrestricted vessels, such as open bowls, both interior and exterior surfaces are scanned. Up to 12 scans are taken of the vessel from different views (sides, top, bottom) and these are merged to form the complete model.

The resulting coordinates (a 3D point cloud made up of individual x, y, and z coordinates) are fitted with a triangulated mesh and surface using the Cyberware software. The resultant 3D model of the ceramic vessel may be fully rotated in all directions for close examination of features on the surface (Fig. 1), not just the *appearance* of 3D obtained by animation of a series of 2D images as in QuickTime VR.

The high-resolution 3D model is retained for archival purposes, as in the case of a highly complex and individually shaped Salado Red effigy jar (Fig. 1) that has been preserved through 3D scanning. A copy of the 3D model file is reduced in size through a process called decimation (reducing the number of triangles to those essential to defining the object) to make it more manageable in the analysis software. The decimated file retains the necessary data to define the 3D form in detail.
The Ceramic Analysis Program, developed by PRISM, computes dimensions of vessels that have a central axis of rotation (Bae 1999). The analysis program automates traditional 2D measurements, but also uses innovative 3D approaches to the measurement of curvature and symmetry, which are the focus of this paper.

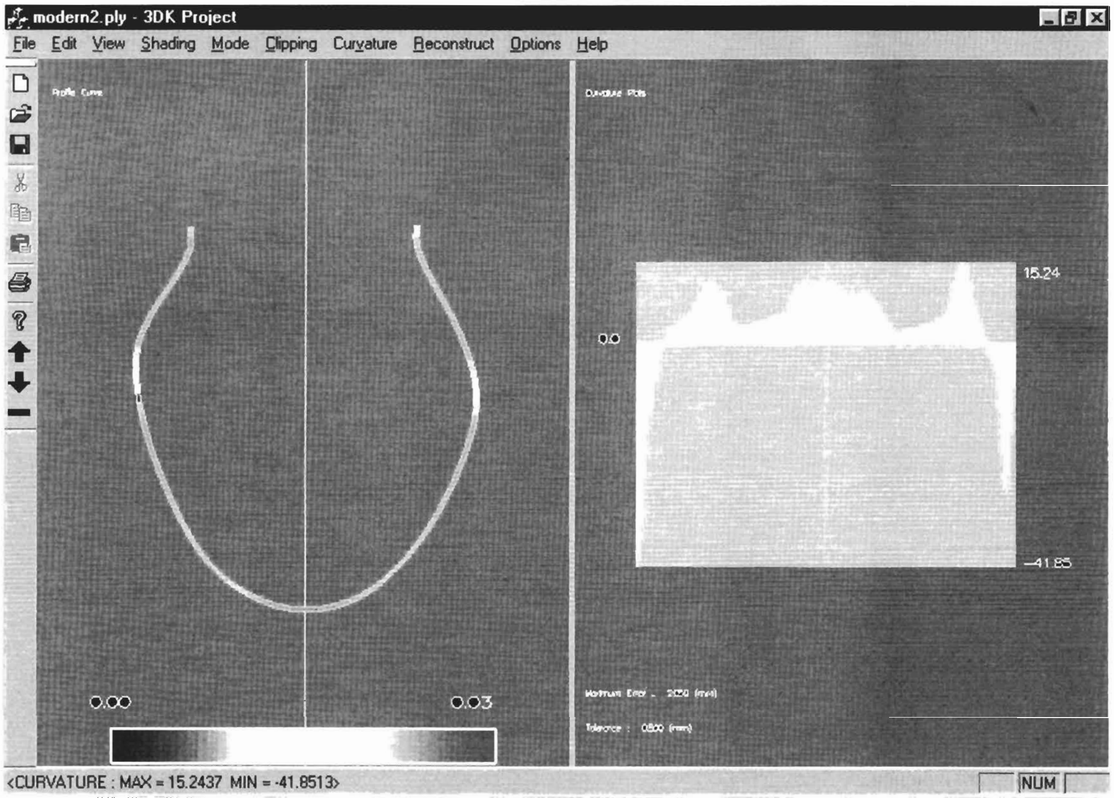

Figure 2 llustration of a *profile curve* (left) and a *curvature plot* (right) of a pottery jar extracted from a 3D model (the PRISM Ceramic Analysis Program).

Curvature As most ceramic vessels have a vertical axis of rotational symmetry, a *profile curve* (i.e., vessel profile) is obtained by cutting with a vertical cross-sectional plane through the vessel (Fig. 2). The archaeologist controls the placement of three orthogonal planes to help create a cutting plane best representing the profile of the vessel. The resulting string of points is fitted with a least-squares cubic (degree 3) B Spline curve within a certain tolerance (Farin 2001a,b).
The number of control points and the parameterization of the B Spline curve are automatically computed (Farin 2001a,b). This is done for two reasons: a) to smooth out the noise in the data, and b) to represent the profile curve as a mathematical representation for which it is easy to compute first and second derivatives, which are needed ultimately to compute the curvature plot of the profile curve.
The *curvature plot* (Fig. 2) of a curve represents how the curve bends and flattens. The curvature plot is an established instrument in industrial design of shapes (Farin 2001a,b); in this paper we are not using it for design purposes, but rather for shape analysis. The curvature plot of the curve is its dual; i.e., given the curvature plot, one can recreate the curve (barring position and rotation in space), however, we use it because there is important information about the curve that is easily seen in its curvature plot, but not from the curve itself.
Since the profile curve is a planar curve, we can assign a sign to the curvature; i.e., positive or negative. Where the curvature plot crosses the zero line is called an *inflection point*, a significant point on the curve that tells precisely where the curve changes from being convex to concave, or vice versa.

Inflection points and *corner points* (i.e., points of high curvature) are important diagnostic features (Fig. 2) that one can only subjectively deduce from looking at the curve, but are easily detected from the curvature plot.

Symmetry Symmetry can be examined by mathematically comparing the two halves of the *curvature plot*. If the vessel is highly symmetrical, the two halves will not differ, but if the vessel is uneven, there will be considerable differences between the two. Based on the curvature plot, *symmetry* is scored on a standardized scale (1 = high and 0 = low):

Let $f(x)$ be a (nonzero) function defined over $x \in [0,1]$. If f is symmetric with respect to $t = 1/2$, then $f(x) = f(1-x)$. A measurement σ for the symmetry of f is given by

$$\sigma f = \frac{\int_0^1 [f(x) - f(1-x)]^2 dx}{\int_0^1 [f(x) + f(1-x)]^2 dx} \tag{1}$$

Further, a unit measurement σ' for the symmetry of f is defined by

$$\sigma' f = 1.0 - \sigma f \tag{2}$$

Thus $\sigma' f = 1$ for a symmetric function.

Using this approach, the software developed by PRISM allows the quantification of the symmetry of 3D forms based on user-defined cross-sections. The symmetry measure is based on a difference in area between the two halves of the graph of the magnitude and direction of curvature (i.e., the *curvature plot* shown in Figure 2).

Results and Discussion

After the successful completion of a pilot study using contemporary vessels as control pots, we conducted symmetry analysis of a selected number of prehistoric vessels (Table 1). Each vessel was analyzed using the Ceramic Analysis Program and results compiled for four different cross-sections (one arbitrarily chosen, one perpendicular to that, and two at oblique angles). The summary statistics for these symmetry measures were calculated for each vessel (Table 1); the standard deviations and coefficients of variation (C.V. = (std dev/mean)*100) clearly show that some vessels have low symmetry measures and high intra-vessel variation indicating less-controlled construction, while others exhibit high symmetry measures and low internal variation indicating highly skilled and controlled construction.

Both low and high symmetry measures are found among the Red/Smudged bowls and jars produced by Salado potters of central Arizona and the Ramos and Capulin polychrome jars produced at Casas Grandes in Chihuahua, Mexico (Table 1). Although products of some highly skilled potters are present in each group, there are other products produced by less skilled potters, indicating a range of skill levels and perhaps time devoted to the craft in each community. Summary statistics for each vessel group (Table 2) indicate that some vessel categories and types exhibit more inter-vessel variation than others. A larger representative sample of vessels within these types and from various sites will be necessary to identify the work of master potters and evaluate these trends in more detail.

Nevertheless, this initial study indicates the usefulness of this approach in providing a quantitative measure of symmetry as a proxy for finely developed production techniques and potters' skill levels.

3D Symmetry

To further investigate intra-vessel symmetry in three dimensions, the Ceramic Analysis Program allows one to generate an idealized 3D vessel based on a selected cross-section, this is then fitted with an overlay of the actual 3D vessel scan to produce a composite (Fig. 3). The contrast between the real and the ideal models visually identifies areas of deviation in the 3D composite. This approach provides a detailed look at the unevenness of the rim, body, and base of the vessel as it is rotated. Results may vary with user choice of the profile selected for generation of the idealized model. However, the user may sample the real model more than once to obtain representative views for merged composites.

Table 1 Symmetry statistics for individual ceramic vessels; the Red/Smudged bowls and jars are from the ASU Roosevelt Platform Mound Study (RPMS) in central Arizona and the Ramos and Capulin polychrome vessels are from the ASUcollection from the Casas Grandes site (Chihuahua, Mexico).

Type			Symmetry					
	Specimen No.	Site No.	Profile No.	Mean	Minimum	Maximum	Std. Dev.	C.V.
Red/Smudged Bowls								
	27796	U:8:450	4	0.68	0.24	0.98	0.32	0.46
	27411	U:8:450	4	0.80	0.55	0.99	0.20	0.25
	30282	U:8:450	4	0.84	0.39	0.99	0.30	0.36
	27528	U:8:450	4	0.88	0.60	0.99	0.18	0.21
	23953	U:8:25	4	0.89	0.75	0.97	0.10	0.11
	29523	U:8:450	4	0.89	0.59	0.99	0.20	0.22
	32231	U:8:450	4	0.92	0.79	0.99	0.09	0.10
	29504	U:8:450	4	0.94	0.79	0.99	0.10	0.11
	34031	U:8:25	4	0.97	0.95	0.98	0.01	0.02
	29525	U:8:450	4	0.97	0.92	0.99	0.03	0.03
	33996	U:8:25	4	0.98	0.92	0.99	0.04	0.04
	34050	U:8:25	4	0.99	0.99	0.99	0.00	0.00
Red/Smudged Jars								
	27815	U:8:450	3	0.48	0.23	0.77	0.27	0.57
	30077	U:8:450	4	0.59	0.25	0.85	0.25	0.42
	27811	U:8:450	3	0.66	0.63	0.70	0.04	0.06
	24587	U:8:25	4	0.81	0.42	0.96	0.26	0.32
	34048	U:8:25	4	0.84	0.54	0.97	0.20	0.24
	17806	U:8:24	4	0.88	0.79	0.98	0.08	0.10
Ramos Polychrome Jars								
	1968.006.00038	C.G.	4	0.70	0.51	0.88	0.16	0.23
	1968.006.00151	C.G.	4	0.80	0.58	0.98	0.16	0.20
	1968.006.00150	C.G.	4	0.89	0.78	0.96	0.09	0.10
	1968.006.00155	C.G.	4	0.91	0.88	0.94	0.03	0.03
	1985.001.00039	C.G.	4	0.96	0.90	0.99	0.04	0.04
	1968.006.00051	C.G.	4	0.97	0.95	0.99	0.02	0.02
	1968.006.00152	C.G.	4	0.97	0.95	0.99	0.03	0.03
Capulin Polychrome Jars								
	1968.006.00145	C.G.	4	0.61	0.49	0.74	0.13	0.21
	1968.006.00053	C.G.	4	0.88	0.73	0.98	0.12	0.13
	1968.006.00143	C.G.	4	0.90	0.84	0.96	0.06	0.06
	1968.006.00149	C.G.	4	0.95	0.90	0.99	0.04	0.04

Note: C.G. is Casas Grandes, other sites are from ASU RPMS.

The PRISM team is currently developing and testing algorithms to quantitatively measure 3D variations in symmetry based on these composite overlays of real and idealized vessels. Further software tools are being developed to facilitate quantitative segmentation of the vessel form into appropriate sub-regions (e.g., neck, body, base) and features (e.g., appliqués, handles, feet). These will allow comparisons of curvature and symmetry of selected vessel regions among pottery collections (cf. Van der Leeuw *et al.* 1991). Such studies will advance our ability to measure and quantitatively compare products of past craft specialists and non-specialists.

Table 2 Summary of symmetry statistics for the ceramic types and vessel forms detailed in Table 1.

	Minimum	Maximum	Mean	Std. Dev.	C.V.
Red Smudged Bowls	0.68	0.99	0.90	0.09	10.0
Red Smudged Jars	0.48	0.88	0.71	0.16	22.3
Ramos Poly. Jars2	0.70	0.97	0.89	0.10	11.5
Capulin Poly. Jars	0.61	0.95	0.84	0.15	18.3

Note: Red/Smudged vessels are from the ASU RPMS project. Ramos and Capulin polychrome are from the ASU Casas Grandes collection.

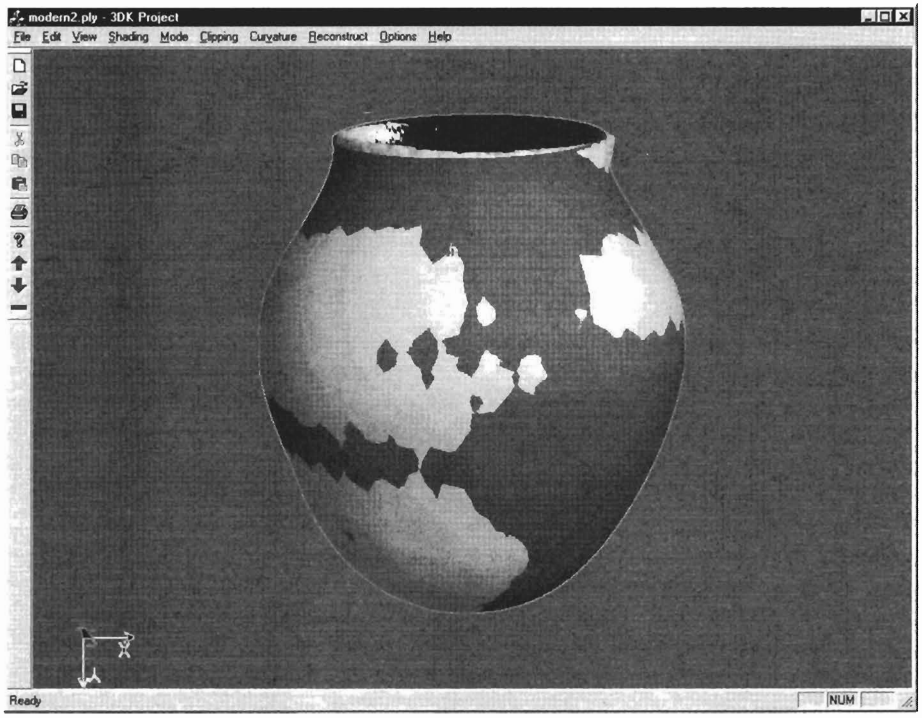

Figure 3 Illustration of merged composite based on real and idealized (generated from a selected profile curve) 3D vessel models, to illustrate the variation in curvature (the PRISM Ceramic Analysis Program).

Conclusion

Recent advances in 3D scanning applications and CAGD modeling include the capturing of detailed and accurate point cloud data (x, y, and z coordinates), surface texture mapping, and curvature modeling. With further analysis using customized analytical software developed by PRISM, quantitative measures such as volume and symmetry can be obtained.

Access to 3D scanners, equipped to capture data on different sized objects, is becoming more economically and technologically feasible for researchers in many disciplines. Although the capability to capture 3D data and amass archives of the scans is a first step to digital preservation and study, only being able to look at such collections of 3D models is not enough. The availability of 3D scanning and archiving challenges researchers to advance conceptual and analytical frameworks to include 3D forms and to go beyond the limitations of traditional 2D representation and measurement.

For 3D archives to provide accurate modeling of 3D forms and help preserve and study the aesthetics and technology of the ancient material culture traditions calls for mathematical definition of diagnostic morphological characteristics and appropriate dimensional measurements. In contrast to highly uniform, contemporary engineered and manufactured objects, access to novel (i.e., non-uniform, or irregular, or organic) datasets for surface fitting and feature classification allows computer scientists to rigorously test surface fitting and feature recognition and classification algorithms.

The resulting 3D data of prehistoric pottery are appropriate for archiving and quantitative analysis of curvatures, volumetrics, proportionality, and symmetry of 3D vessel forms. The 3D digital models can be used to examine the symmetry and uniformity of prehistoric ceramic vessels as indicators of potter's skill levels. Such detailed examinations will aid assessments of the development of craft specialization and social organizational complexity among prehistoric Southwest cultures. Additionally, providing web-based digital access to the vessel form models and measurements allows wide audiences of researchers and the interested public to benefit from such research.

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