A 3D Digital Library System: Capture, Analysis, Query, and Display

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Abstract:

This paper describes development of a storage, archival, and sketch-based query and retrieval system for 3D objects. The process and results provide a model for a Digital Library of 3D data for further study and analysis. The initial focus has been Native American ceramic vessels, scanned and defined as a set of three-dimensional triangulated meshes composed of points and triangles. The process involves modeling the data with parametric surfaces, and extracting relevant features to raise the level of abstraction of data. The project uses a class based XML schema to catalog and organize vessel data. A visual query process was developed to permit users to interact with the data using sketches or by selecting sample vessel shapes to augment text and metric search criteria to retrieve original and modeled data, and interactive 2D and 3D models.

Keywords:

Digital Library, Geometric Modeling, Image Databases, Information Visualization, Physically Based Modeling, Scientific Visualization, Shape Recognition, WWW Applications.

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1. Introduction

The 3DK project at Arizona State University has developed a system that creates a robust set of 3D descriptive about cultural artifacts. The cataloged descriptive information is housed in a database that permits researchers to dynamically interact with the data. The result is a digital library that is significantly more complex than both traditional collections of text, and even graphic and photographic image collections.

Data acquisition begins with a relatively amorphous 3D point cloud of data produced by scanning the original artifact. Software developed by the project team then models, measures, catalogs, and stores the data. A flexible, web based query process, and intuitive user interface provide access to this data using a simple vocabulary of tools developed to model, measure, and interact with data in new and powerful ways.

Since inception, physical sciences such as anthropology have used simple measurement techniques to quantify and compare data about samples such as pottery, bones, and lithic tools.

Measurement tools such as calipers, rulers and hand drawn sketches have been joined by computers and global positioning systems to generate more accurate data about artifacts. Typically the focus of these technologies has been to enhance access to tabular descriptive data in flat field databases or to more accurately record the location of the artifacts in maps or diagrams of their original setting.

A collection of Native American pottery was the initial focus of the 3DK project at Arizona State University. Researchers were looking for a method of searching and comparing artifacts within the holdings of the Anthropology Research Institute at Arizona State University. The research problems were twofold:

?? How to model the artifacts to permit more accurate representation and measurement,

?? How to create a system to catalog, query, search, retrieve, and display the data.

The paper will focus on the technical tools developed to acquire the data, and to model and provide cataloging, description, and interactive access to the 3D models, and to the existing 2D textual and descriptive data that describes artifact provenance and context.

The 3DK team developed a set of mathematical modeling algorithms to pass surfaces through scanned point cloud data to generate measurable data from these relatively small, diverse data sets. Surface and volume modeling algorithms were then developed and applied to model and generate quantitative, descriptive data about the artifact. The data and processes developed grew from and are consistent with the descriptive vocabulary of ceramics researchers in Anthropology. The level of accuracy in documentation and measurement of the artifacts far exceeded traditional techniques used in the field. The binary and derived data about the vessel provides a record that can be re-analyzed in the future and provide a tool for research without physical access, at remote locations, or after repatriation.

The original scanned data, and the modeled and calculated data have been linked to existing records sets containing the traditional descriptive data about location, provenance, and collection. An XML schema using a metadata schema derived from the Council for the Preservation of Anthropological Records (COPAR). The schema defines data elements for a given artifact, and links data across multiple databases was developed and implemented to support research queries.

The final component is a web client interface that permits researchers to interact with the data through a sketch-based query system. The interface permits the user to manipulate a representation of the data and query the data sets by a combination of features extracted from this representation and textual and metric data. This system provides researchers with a powerful, interactive prototype digital library of ceramic vessel data.

Efforts to date have focused primarily on the acquisition and modeling of the ceramic vessel data. Development of the artifact database and user interface have progressed to the point of “proof of concept”. The project will continue development and research into metadata and data description, criteria and weighting of search results, and continued development of the interface design and interactive capabilities.

In its current state, the 3DK process provides a model for analysis and exploration of issues and the complexity of digital collections of 3D data. The overview of the processes, design assumptions, and products provides a prototype for discussions of the issues and identification of necessary components for effective design of comprehensive digital collections of new kinds of documents, including complex 3D data.

2. Scanning/Data Acquisition

The project uses two Cyberware scanners, the M15 and 3030 to scan ceramic vessels. While individual scans take only 17 seconds, the total average scanning time for each vessel is about two hours, depending on complexity, color, texture, etc. Currently, scanning has focused on complete (or nearly complete) ceramic vessels from the Classic Period (A. D. 1250 – 1450) of the prehistoric Hohokam culture area of the Southwest (Salt/Gila River Valleys) near present-day Phoenix, Arizona. The ceramic vessels are part of the Roosevelt Platform Mound Study collection and the Department of Anthropology Whole Vessel collection curated at the Archaeological Research Institute (ARI) at Arizona State University.

The scanning produces data as a highly dense point cloud. Post processing involves filling of holes (due to scanner “oversight”), removing noise, etc. The project team has implemented its own version of the Ball Pivoting algorithm (Bernadini et al, 1999) to convert point cloud data sets into triangle meshes. In some cases light decimation is performed to reduce the density without losing accuracy of the overall structure. The result is valid point set and topology data for each scanned vessel.

To date, 80 vessels had been scanned, processed, and archived in the database. Future efforts include exploring techniques to scan the interior of complex vessels, and scanning pottery shards to obtain data to attempt to reassemble and recreate original vessel shapes with missing pieces.

3. Modeling and Measurement

The initial modeling technique used is Feature Extraction or Segmentation. The 3-dimensional (3D) triangular mesh data is segmented or broken down into subsets of vertices. The goal is to simplify the mesh data and create regions that are “meaningful” for applications or to users. The feature extraction algorithms developed to model and measure the vessels are more effective working from higher point density mesh data. Mesh segmentation has numerous applications, most notably in feature extraction, reverse engineering, mesh reparameterization and adaptive schemes for techniques such as decimation and subdivision.

The project uses a *watershed segmentation* scheme (Mangan and Whitaker), that appears prominently in image segmentation literature but has only recently been applied to the 3D mesh segmentation problem. The watershed scheme gets its name from the concept of imaginary water droplets traveling downward along the height function under the influence of gravity. The segmentation is based on curvature, and therefore several curvature estimation techniques have been implemented and analyzed. The robustness of segmentation has been improved by increasing the accuracy of the curvature estimates.

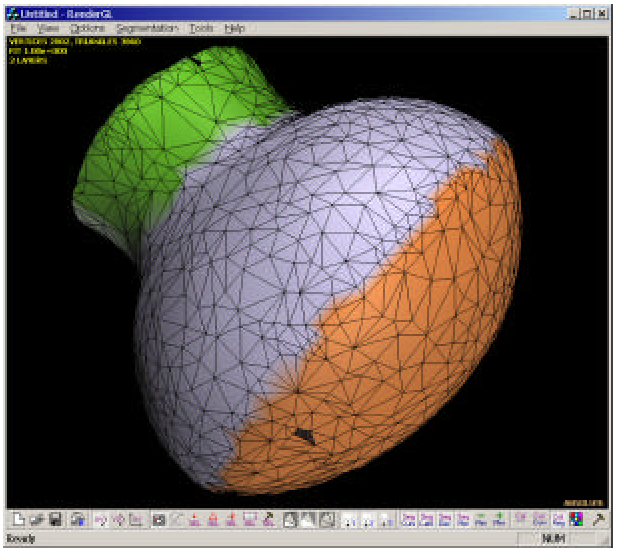

Figure 1. Polygonal Mesh with watershed defined areas for complete vessel.

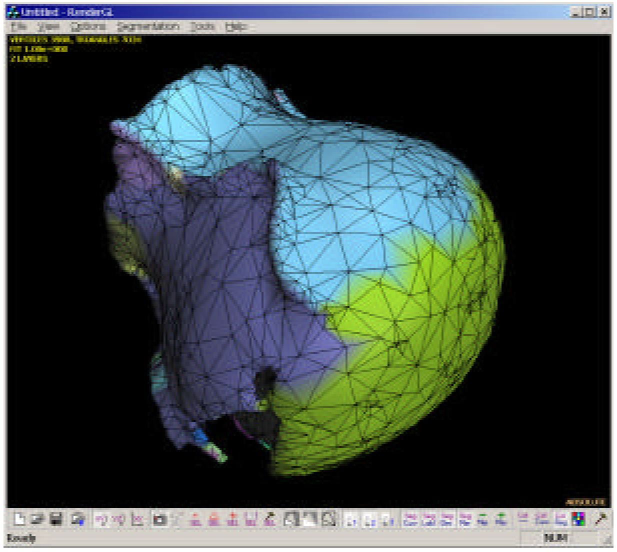

Figure 2. Polygonal Mesh with watershed defined areas for partial vessel.

While Mangan and Whitaker's implementation produces accurate results only on simple smooth surfaces, the implementation in this research successfully segmented several real world data sets like the ceramic vessels. The watershed algorithm is based on a scalar value (called the height) assigned to every mesh vertex which captures some essence of the local mesh shape. The height at a vertex is typically the curvature of the mesh at that vertex. The scheme groups all vertices on the paths of droplets that would, in concept, converge at the same location into a single region. The segmentation results in defined regions of relatively consistent curvature separated by vertices with high curvature (which act as boundaries).

Due to the accuracy required for good segmentation, computing curvature is a complex, non-trivial task. In this research, multiple curvature estimation schemes are used and compared. The estimation schemes can be broadly classified into two categories - discrete and continuous. Discrete schemes extract curvature directly from the geometry of the mesh by estimating the local deviation of the mesh from a flat surface. Continuous schemes first approximate the mesh vertices locally with a polynomial surface, allowing calculation of various forms of curvature from the resulting analytic surface by methods of differential geometry (Pulla, 2000).

3.1 Geometric Modeling – Surface:

As noted earlier, the result of the 3D laser scan of the vessel and initial processing is a polygonal mesh composed of faces, edges and vertices and their connections. Surface models are generated from the scattered points of this polygonal mesh by least squares fitting and/or rotating profile curves. B-Spline surfaces are used to represent these surface models. The B-Spline models are used for model rebuilding, error analysis, closing holes and gaps found on the archaeological artifacts, and measured value getting.

Another important tool used to analyze archaeological vessels is contour shape information. Two kinds of models, chain codes and B-Spline curves have been used to represent profile curves of archaeological vessels. For the vessels used in this project, several problems of 3D analysis can be addressed and simplified using 2D geometric models. For example, 2D chain codes can be generated by intersecting a cutting plane with the 3D polygonal meshes representing the vessels. B-Spline curves, can then be derived by interpolating points of chain codes. Because measures of curvature such as convexity, smoothness, and inflection points of the curve are needed for vessel analysis, we have chosen cubic B-Spline curves to approximate profile curves of vessels. The accuracy of these derived curves far exceeds the manually sketched or mechanically derived curves currently used to describe these vessels.

In summary, the procedure of geometric modeling can be described as a seven step process once the point cloud data from scanning the vessel has been obtained:

?? Preprocess/noise removal

?? Obtain profile curves (represented by chain codes) from 3D meshes

?? Interpolate chain codes by B-Spline curves

?? Compute signed curvature pilot of the B-Spline curves

?? Analyze curvature pilot to get feature points (End Point, Inflection Point, Vertical Tangent, and Corner Point)

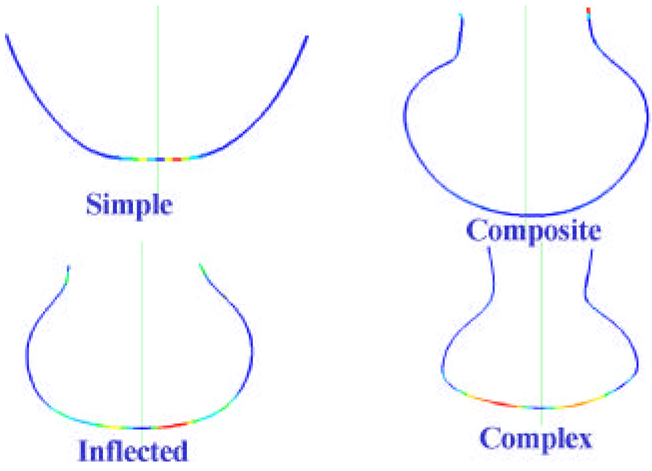

Figure 5. Vessel shape categories The first and last points on the resulting profile curve are labeled end points. A center point for the curve is determined and the curve is walked to left and right of this point to determine local minimum and maximum values. The changes in curvature are evaluated and

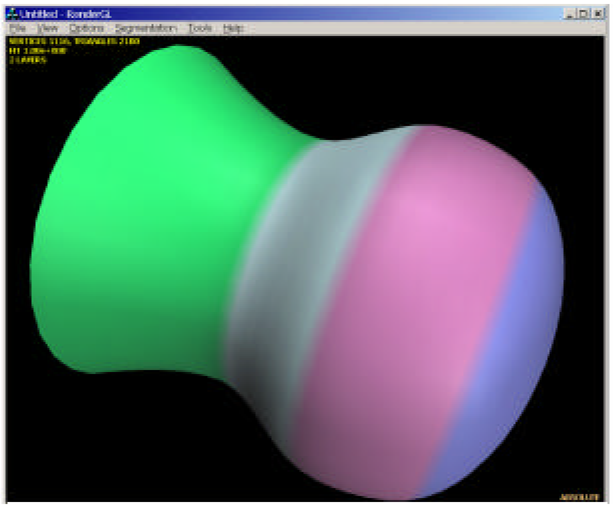

Figure 3. Feature segmentation of complex shaped vessel.

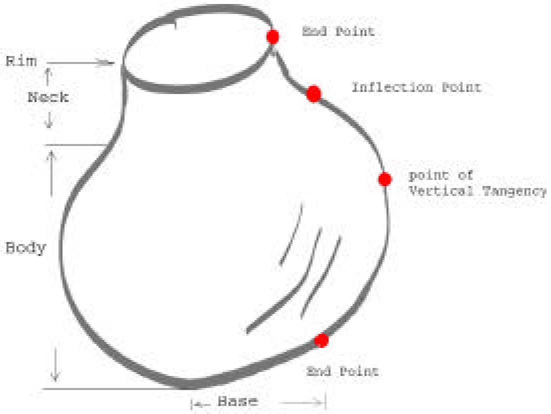

Figure 4. Descriptive elements of ceramic vessel.

?? Derive region features (rim, neck, body, and base) from feature points

?? Re-generate vessels (represented by B-Spline Surfaces) by rotating profile curves and/or interpolating 3D meshes

The result of the feature segmentation and modeling processes is a representation of the ceramic vessel broken down into measurable regions meaningful to archeologists.

Archaeologists analyze vessels by defining various regions using a profile. The profile curve is obtained by passing a vertical plane perpendicular to the base through the vessel. Typically profile curves are sketched free hand, often by tracing and duplicating half of the vessel to create a symmetric, but not necessarily accurate, representation. In this research the polygonal mesh model is used to generate a much more accurate profile curve than has been previously possible.

The resulting profile curve is processed to remove noise due to scanning error at the rim. Vessels are initially cataloged into four broad shape categories - simple, composite, inflected, and complex.

4. Data Storage

To provide efficient access, the project team developed a scanned vessel data. The database was structured to house the original binary data files, modeled files, derived measurement, features, and other descriptive data. A master pot identification number has been used as the key to link these data elements with additional vessel data in existing databases.

This model permits additional databases to link to the query engine by adding a field with the master pot ID to each record set, and developing an XML schema and DTD to link related data fields between the databases. Ideally, data definition and database design standards for vessels will develop over time. In the meantime, this technique is scalable as a proof of concept, is consistent with Dublin Core cataloging structures, and requires minimal coding to provide access to additional databases.

5. Visual Query Interface

The query process combines a sketch-based interface and searches by traditional text and metric data. Representative vessel shapes can be selected from the supplied palette and modified, or a freeform profile sketch can be created in the interface window. Text and numeric fields support parallel query of descriptive and derived data within the databases.

The Visual Query system we have created permits users to input, analyze, refine and limit searches via interaction with a Graphic User Interface (GUI). The initial query request can be made in a variety of modes including text, vector graphics, and interactive 2D and 3D models. The user can manipulate and resubmit the query image in real time to refine searches. The interface includes fast interactive surface and volume visualization capabilities and quantification tools to extract curvature, volume, scale, and linear dimensions for each data set.

The research intent for the interface is to enable the highest degree of interactivity possible with complex 3D data while avoiding steep user learning curves. This means

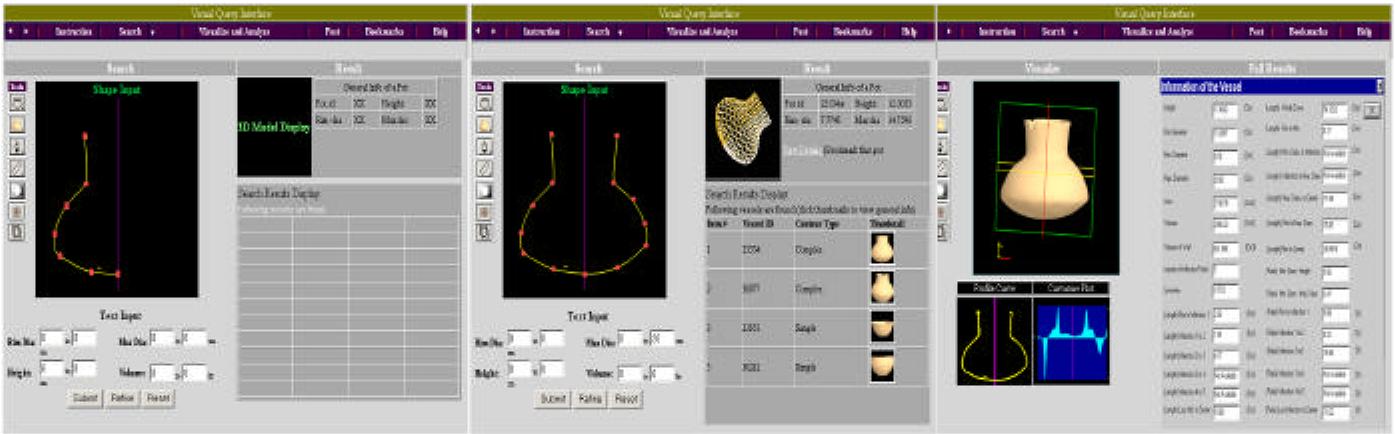

Figure 6. (L to R) Query interface screen with sketch–based, numeric, and text-based input fields. Initial response screen with resulting thumbnail images and summary data, and wire frame of first matching vessel. Detail individual display screen with 2D, 3D, and descriptive vessel data.

understanding not only the science and art of interface design, but developing an appreciation of the cognitive complexity of the user's dynamic relationship to the databases. The prototype interface design is currently being evaluated by web designers, anthropologists, and general users. As additional models , such as lithic and bone data become available the interface, and related tool sets and capabilities will continue to evolve.

6. The Query Process

Behind the interface is a process that extracts key elements and manages submission of the queries to the related databases. After search information has been entered and the query submitted to the server, a Java program extracts features from the sketch. A CGI program parses, manages, and executes searches in the linked databases. The program currently matches text, numeric and calculated vessel data. The capacity to more abstractly search and match by pattern within the binary data is being explored and will be added as the project continues to develop.

The results of the search from the linked databases are compiled and tabulated. A Java Server Program subsequently sends the processed search results to the client as an XSL file. This XSL file contains thumbnail images and descriptive data for the top 5 vessels in the search results. The XSL file provides the user's browser with the data needed to view detailed information for any of the 5 vessels without need for further interaction with the server and databases.

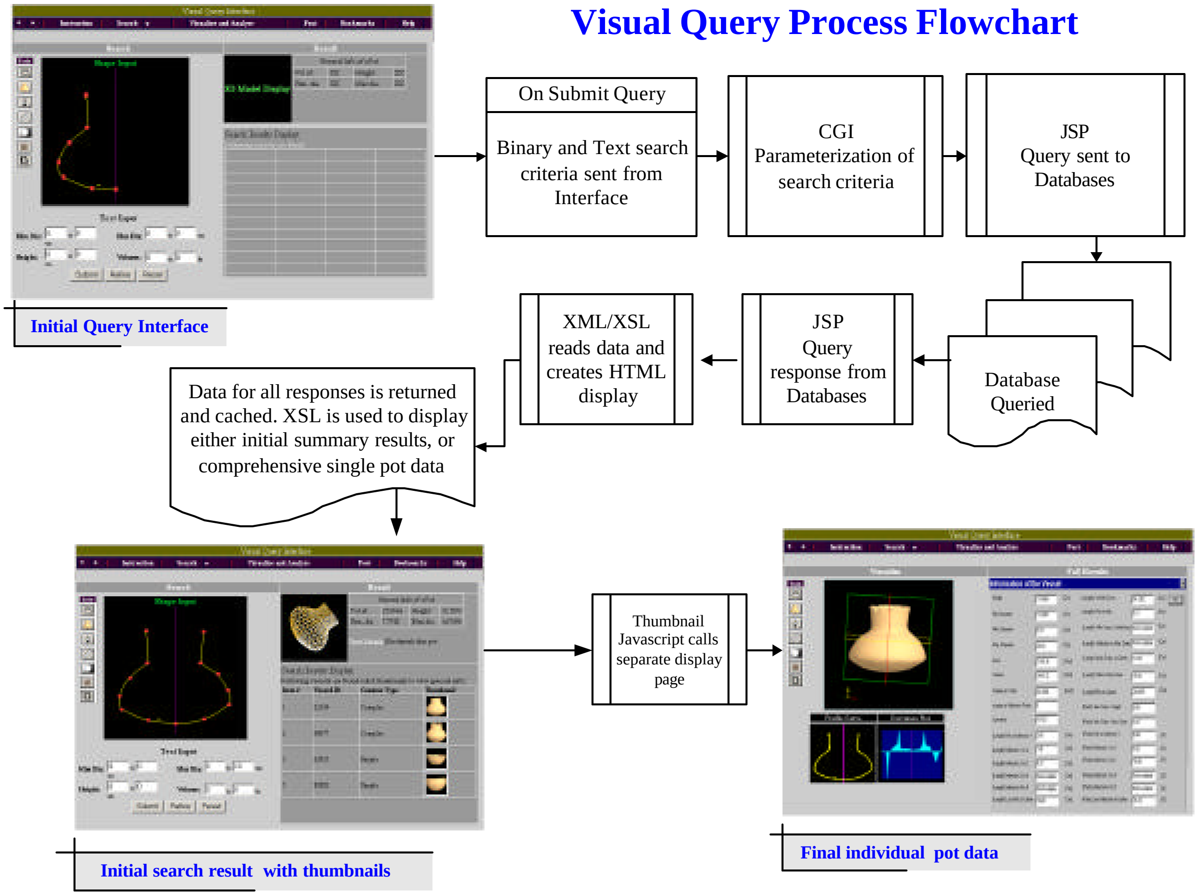

Figure 7. Summary of the query-search-retrieval process.

When the search results are sent from the server, the client browser extracts and displays thumbnail and summary data from the XSL file on the initial search result screen. The user can then select one of the thumbnails from the display. This action prompts the client to extract and display a both manipulable 3D model of the selected vessel and detailed descriptive data.

Currently, modification of the query sketch requires returning to the initial search result or new search screen. We are still grappling with how to bookmark or store search results to create a traceable research trail over time or multiple searches.

7. Future Directions

Several future directions for this phase of the project have been noted earlier, including exploration of scanning to obtain internal vessel data, pattern based searching, and refinement of the interface. In addition, the extraction, modeling and cataloging process developed in this research is scalable and will hopefully expand to incorporate vessels from other collections. Vessels can be scanned, and the resulting point cloud data can be processed and incorporated with existing descriptive data in local databases. These databases can be linked and made available to the query interface to expand the universe of material available to the researcher. The cataloging and descriptive data can also describe ceramic vessels from other time periods and further expand the research capabilities of this system. The current proof of concept model can be the foundation of a production level project to create a true digital library of vessel data.

This team plans to expand and explore several other types of 3-dimensional data as part of this research effort including: lithic tools; features of bones, such as condyle surfaces, spines, and facets; 3D ultrasound data; DNA structures in fertilized mouse eggs; and diatom shapes. The goal is to broaden the modeling, cataloging and description tools and to refine the visual query interface. Refining descriptive elements and metadata, and addressing the archival issues required to provide access to this information over ime will be additional research areas to be pursued.

One further goal is to extend the operability of the web-based interactive model across platforms. As we are able to optimize code, relatively small bandwidth will be required, making remote access to the digital collections possible. Desktop processing power supports the current model making it available to a broad potential audience. In addition, incorporating a wide variety of user inputs such as graphic tablets, touch screens, and other biometric control devices will ensure the widest possible use of the system--from underrepresented groups such as the disabled community, to high school science classes, to discipline-based researchers.

Evaluation, review and revision of the query interface will continue. The underlying query process will be evaluated by assessing the efficiency of the search procedures. To be an effective digital repository and viable research tool, the query system must be robust and reliable enough to provide consistent, replicable searches over time. User satisfaction with query interface, structure, and organization will also continue.

The assessment team and the other members of the project interact in an ongoing internal feedback loop that provides formative information about the effectiveness of the overall effort and of the individual project teams. Summative evaluation will show the effect of constant system refinement from the ongoing formative evaluation.

8. Conclusion

This project has successfully developed a powerful system of 3D modeling and analysis techniques to provide descriptive data and support research into vessel shape and structure. It is interesting to note that even measurements that are relatively coarse from a computer science modeling perspective offer significant improvements in accuracy for ceramic researchers. The ability to search and compare these accurate models of vessels offers new tools to ceramic vessel researchers.

The project also addresses an increasingly important research limitation for these artifacts – the loss of access to the due to Federal mandates to return the artifacts to the descendents of their creators. During the past decade repatriation of artifacts has significantly influenced research access to collections and impacts the level of detail required when archaeologists record data for future reference. Only the photographs, sketches, and reference data remain for future researchers.

The system of 3D processes developed by this project capture and maintain accurate data, and 3D representations of these artifacts, creating a digital library of data about the artifacts for future use and appreciation by researchers, Native Americans, and the general public.

9. Acknowledgements

This has been a truly interdisciplinary project and the successes result from a dynamic interaction between researchers in a broad range of disciplines at Arizona State University. This work was partially funded by the National Science Foundation KDI: 3D Knowledge: Acquisition, representation & Analysis in a Distributed Environment (IIS-9980166), and support form the Arizona State University Vice Provost for Research, Vice Provost for Information Technology, and Deans of the Colleges of Engineering and Applied Sciences, Liberal Arts, and Fine Arts. Project team members and additional information is available at the Partnership for Research in Stereo Modeling (PRISM) site: http://3dk.asu.edu/DOCUMENT/research/3dkresearch.html.

10. References

Bae, M. (1999). Curvature and analysis of archaeological shapes. Master Degree Thesis, Arizona State University.

Bernadini, F., Mittleman, J., Rushmeier, H. Silva, C., Taubin, G. The Ball-Pivoting Algorithm for Surface Reconstruction, IEEE Transactions on Visualization and Computer Graphics, Vol. 5, No. 4, October/December 1999.

Birkhoff, G. D. (1933) Aesthetic Measure, Cambridge.

The Council for the Preservation of Anthropological Records, (**CoPAR**), http://copar.asu.edu/.

Farin, G. E. (1996). Curve and Surface for Computer Aided Geometric Design. Academic Press, Boston, fourth edition.

Mangan, A. and Whitaker, R. Partitioning 3D Surface Meshes Using Watershed Segmentation, IEEE Transactions on Visualization and Computer Graphics, Vol.5, No. 4, Oct-Dec 1999.

Mukaiyama, Hiroshi, Technical Aspect of Next Generation Digital Library Project , Proceedings of the International Symposium on Research, Development and Practice in Digital Libraries : ISDL'97

Pulla, S. (2001). Curvature based segmentation of 3-dimensional meshes, Master Degree Thesis, Arizona State University.

Rice, P. (1987). Pottery Analysis: A Sourcebook. University of Chicago Press, Chicago.

Shepard, A. (1976). Ceramics for the Archaeologist. Carnegie Institution of Washington, Washington, D.C.