Advances in Geometric Modeling and Feature Extraction on Pots, Rocks and Bones for Representation and Query via the Internet

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Abstract: This paper outlines progress on the 3D Knowledge and Distributed Intelligence project (3DK) at Arizona State University. Three of the six 3DK pilot projects involve archaeological and biological material, namely ceramic vessels, lithic artifacts, and bones. These projects are: (1) "3D Morphology of Ceramic Vessels" which aims to learn about vessel uniformity and proportionality as indicators of developing craft specialization and complex social organization among prehistoric cultures; (2) "Lithic Refitting" which intends to develop the algorithms required to (partially) automate the refitting process through 3D scanning and surface modeling; and (3) "3D Topography of Joint Surfaces" which investigates the ability of human ancestors to make tools and walk upright. This paper discusses underlying research aspects common to all three pilot projects: data acquisition, modeling, feature recognition, database construction, and development of a visual query interface aimed at making 3D models of these artifacts available online for query.

Key words: 3D; modeling; query; archiving; feature extraction; ceramics; lithic refitting; joint surfaces

Introduction

Recent theoretical and technological breakthroughs in mathematical surface modeling and data-capturing techniques present the opportunity to advance 3D knowledge into new realms of cross-disciplinary research. The focus of PRISM's 3D Knowledge (3DK – http://3dk.asu.edu/) project is to research and develop the acquisition, representation, query and analysis of 3D information within a distributed environment such that researchers in many fields can exploit the full potential of 3D objects and phenomena.

The understanding of 3D structures is essential to many scientific disciplines, including archaeology and physical anthropology. For example, (1) archaeologists study the 3D form of Native American pottery to characterize the development of prehistoric cultures; (2) Lithic researchers conjoin the remains of individual lithic reduction sequences to understand the development of stone tool technology over time; and (3) Physical anthropologists compare 3D joint surfaces of human and nonhuman primate bones and study the effects of surface area, curvature, and congruency on the mechanics of a joint to reconstruct manipulative and locomotor behavior of early humans. To date, the methods that anthropologists use to measure, record, and classify 3D data such as calipers, photographs, drawings, and the use of classification schemes that reduce objects to simplified descriptors are inadequate for accurately representing such complex data. Within the past decade, improved technologies for capturing 3D objects have emerged, offering the possibility to obtain and store accurate mathematical models of objects in digital form.

At the heart of the 3D-knowledge environment are the kernel, the user interface, and the data archiving (Figure 2). The system enables user-access to archived 3D data at multiple levels of abstraction. The power resides in its ability to accept queries posed in a variety of forms and at high levels of abstraction and return the results as visualizations of the 3D objects and phenomena. Queries take the form of text, numerical data, visual primitives, and hand sketches. Input to the 3D Knowledge kernel is made through a variety of methods and agents including object segmentation, feature extraction, feature analysis and correspondence, indexing, and relationship to other objects. The 3D knowledge extraction phase of the project is the most challenging one to implement. The filtering of the representation from raw data to knowledge in the 3D Knowledge Kernel comes from the joint interaction of archaeologists, computer scientists and engineers to enable definition and query of features. To facilitate use among a broad range of researchers, instructors and students, the 3D Kernel visual query interface is accessible via the World Wide Web at http://3dk.asu.edu. Further, this research aims to develop a universal vocabulary of cognitive pattern primitives (CPPs) and an algebra (Feature Algebra) for defining complex features that cross disciplinary boundaries. We are building upon such feature extraction and representation methods in order to create a robust 3D-knowledge environment.

To effectively conduct research using 3D data, one is required to go through a number of steps irrespective of the particular application (Figure 1). This paper focuses specifically on these steps and applies them to the pilot projects involving pots, lithics, and bones.

Pilot projects

3D Morphology of Ceramic Vessels

The aim of the prehistoric ceramic vessel pilot project is to learn about vessel uniformity and variation with respect to function as indicators of developing craft specialization and complex social organization among prehistoric Native American cultures. To accurately capture the complex curvatures and vessel form and size variation, the use of metric rulers and visual inspection of 2D profiles is inadequate. Therefore, scalable, visual, and quantitative comparisons of curvatures have been developed for the study of prehistoric pottery traditions.

Based on 3D scanned data, 2D measurements (height, rim diameter, minimum diameter, maximum diameter) and 3D measurements (area, volume, volume of wall) are generated, and a measure of symmetry is developed (Figure 3). The pilot project uses a control collection consisting of two Mexican flowerpots, two Mexican mold-made piñata pots, and three hand-built Tarahumara jars to verify the validity of the formulas generated. The two prehistoric collections studied consist of a total of 87 Native American vessels from the Tonto Basin in Arizona, and the Casas Grandes in northern Mexico.

The control study and the two sets of prehistoric vessels are used to generate a quantitative analysis of vessel uniformity and symmetry. The automated measurements are important improvements that facilitate the quantitative assessment of ceramic uniformity and standardization, both of which are indicators of the development of craft specialization, differentiation of labor, and the development of complex forms of social organization among prehistoric cultures.

Lithic Tool Manufacture and Refitting

The goal of the lithic refitting pilot project is the reconstruction of stone tool manufacturing activities and related cultural behaviors within prehistoric archaeological sites by identifying sequences of conjoining lithic artifacts. Refitting lithic artifacts by manual trial and error is an accurate, but highly labor-intensive, method that requires the entire sample of artifacts to be present in a single lab. These conditions are not always possible given various antiquities restrictions. Automated 3D surface matching of conjoinable artifacts will dramatically enhance the efficiency of this valuable analytic method and extend the scope of searches to collections from different sites. Lithic refitting, or assembling the pieces of stone, broken apart by prehistoric people, has proven very useful in our attempt to better understand the prehistoric past. The technique is especially useful in technological studies, taphonomic research, and spatial analysis. The 3DK project is developing software that would reduce the time cost of refitting and facilitate development of an electronic database storing 3D images of lithic collections available for study by researchers all over the world. Theoretically, there are two ways to go about refitting. One starts from the core to which the last flakes removed from that core can be fitted (Figure 4). Once fitted, the refit set is regarded as the new core to which still other artifacts can be fitted. The advantage of this approach is that the negative scar on the core fits perfectly with the ventral surface of the detached flake, allowing us to look for a perfect match between two surfaces. However, this approach starts from the unwarranted assumption that all pieces will be complete and even more problematic, that all pieces fitting in the original block are present at the site. Therefore a second approach is needed, one in which we can, not only search for perfect matches, but also search for partial fits between two surfaces.

For this study we are currently using experimental reduction sequences as a test to evaluate and refine matching algorithms. Once the algorithms are developed we will proceed and use the technique on WHS 623X, an Ahmarian (Upper Paleolithic) site from the Wadi al-Hasa in West-Central Jordan. At this small knapping station some refitting has been done, allowing us to evaluate the manual refitting results against computer based refitting results.

3D Topography of Joint Surfaces

The objective of the "3D topography of joint surfaces pilot project" is to further our understanding of the abilities, limitations, and adaptations of our early human ancestors to make tools and walk upright. Developing biomechanical models of manipulative and locomotor behavior using 3D osteological data does this. The use of calipers and visual inspection to capture the complex curvatures of 3D joint surfaces and to control for body size differences in cross-species comparisons is inadequate. We expect to overcome this by developing scalable, quantitative models of reciprocal wrist, hand, and knee joint surfaces that will allow for comparative quantitative analysis of the effect of surface area, curvature, and congruency on joint mechanics in extant and fossil apes and humans.

Since the project inception, more than 600 bones representing the wrist and hand joints of humans, chimpanzees, gorillas, orangutans, and gibbons have been digitized to create a database that will eventually include approximately 1000 bones representing the wrist, hand, and knee joints of humans and apes. With an aim to better understand the functional morphology of joint surfaces, the segmentation of features from a bone that are of particular interest to a physical anthropologist, such as joint surfaces, may be automated, avoiding manual digitization of such features that is both time consuming and labor intensive. The surface areas and curvatures of joint surfaces and the congruencies between reciprocal joint surfaces are then quantified and analyzed. Using this digitized osteological data, combined with musculoskeletal data from cadavers and manipulative and positional behavioral data, static and dynamic models can be built to analyze the mechanics of manipulative and locomotor behavior.

Common elements

This paper focuses on the aspects common to the three pilot projects outlined above. All of these projects deal with digital 3D information and the development of a database structure to make 3D models of artifacts available online for query. These two elements constitute an intricate part of the 3DK research. In the following sections we will discuss five aspects crosscutting discipline specific applications. These are: (1) the data acquisition process, (2) modeling of point cloud data, (3) segmentation and feature extraction, (4) database storage, and finally (5) online display and query. These five aspects make this project truly an interdisciplinary research endeavor as the results of the project will provide contributions in the disciplines involved, such as computer science (specifically computational geometry), engineering, archaeology/anthropology, information technology, and database development research.

Data Acquisition

The 3DK project currently uses two laser scanners for data acquisition: a Cyberware Model 15 scanner and a Cyberware Model 3030RGB/MS scanner. The former is a mobile scanner particularly useful for smaller objects (Figure 6), while the latter is a large stationary scanner, which allows for the capture of large objects. Both scanners are equipped with turntables on which the objects to be scanned are mounted. The objects are scanned horizontally; subsequently the turntable rotates by a user-defined number of degrees, after which the scanners captures more information and so on. After this initial data capture, the resulting scans are manually edited and automatically merged, after which the object is repositioned to scan the bottom and top of the artifact. Finally, the orientations are merged to form the complete 3D image. Different types of objects require more or less scanning time. For example particular types of stone are more or less easily captured depending on the degree of translucence and luster of the artifact as well as the sharpness of the edges. In addition, complex artifact topographies require additional scans and orientations for an adequate 3D representation. As a result scanning time varies considerably depending on the size and complexity of the object ranging from under 15 minutes to two hours for scanning and data cleanup. Resolution and accuracy of the scans are a result of the distance between the scanning head and the object. The large scanner is therefore less accurate than the small scanner. For specifics on the accuracy and resolution of the laser scanners that we use, please refer to http://www.cyberware.com. Resulting from the data capture are sets of ordered point clouds as well as, in the case of the large scanner, a separate data file for color.

Modeling

When an object is scanned using a laser digitizer, several tens or hundreds of thousand point coordinates are generated, each representing a location on the object. This collection of points is referred to as a 'point cloud'. It has no structure and is simply a file containing x ,y, and z values. In order to work with this point cloud data, it has to be structured or modeled. The most common method used is to triangulate the point cloud data points. The result of this process is a collection of triangles having the digitized points as vertices (Figure 7). Each triangle 'knows' about its neighbors, which is the structure that allows fast processing of the geometry represented by the triangulation. It is important to stress that the same set of vertices or data points could have several triangulations. The emphasis therefore, should be on the vertices themselves, rather than the 'surface' as represented by the triangles.

3D triangular meshes are currently a popular surface modeling primitive, used extensively to represent real world and synthetic surfaces in computer graphics. In order to generate meshes, real world objects are often either digitized, as described earlier, or sampled as a volume from which a surface is extracted. Alternately, the points, and their connectivity, can be generated using computer software programs, either interactively (eg using a surface design tool) or automatically from mathematical functions.

Since triangulation is only a modeling primitive, additional modeling steps are necessary. Figure 8 shows the different elements of the geometric modeling module of the 3D kernel subdivided in surface and volume models. Surface contour shape information plays an important role in the analysis of archaeological material. To extract this information modeling is necessary to study the profile curve of a ceramic vessel, or the cross section of a bone, for example. To represent profile curves of archaeological vessels, we use two kinds of models: chain codes and NURBS (Non uniform Rational B-Splines) (Farin 1996; Razdan et al 2001).

Chain codes can be used to extract a 2D profile curve of a vessel. A cutting plane is projected through the 3D mesh and intersection points with the mesh are extracted and ordered in the chain code. These points are then connected to form the profile curve. After chain points are extracted, NURB curves are fitted to the chain using least squares approximations. The result is a profile curve from which appropriate features such as corner points, end points, and symmetry between both halves of the profile curve can be readily computed.

If an object is inherently smooth, it is advantageous to represent it by a smooth data format. The most widely used formats are NURBS. A NURB data set consists of control points arranged in a grid of points, roughly representing a given shape. NURB forms provide a compact data representation making it easy to calculate the curvatures of objects to extract their essential shape characteristics.

Feature Extraction and Segmentation

The next step, after the scanning and initial modeling of the artifacts, is the extraction of appropriate feature data for study. Indeed, the features are the primary goal of the subdiscipline-specific research. Although features such as corner points on a pot, joint surfaces on a bone, and flake negatives on lithics are diverse sets, they can be extracted using a common set of algorithms.

Extraction of features from objects and the use of these features to search for particular shapes involve multiple levels of analysis and extraction algorithms. However, as a common denominator, we assume that features are built from cognitive pattern primitives (CPP) that are essentially the geometrically meaningful feature building blocks. Examples of CPPs include curves, for example a part of a profile curve, and surfaces such as segments of the ventral surface of a lithic. Building features from these primitives requires a construction method, which allows these CPPs to be arranged and connected in various ways and for these connections and arrangements to be described mathematically. A set of CPPs and a set of operators to connect and arrange these CPPs (Figure 9) can then define features. Extracting information from modeled data can take on various forms depending on the desired information. We separate features into four categories: point, curve, surface and volume data. Point, curve, and surface features will be described using examples from the pilot projects. While we have not advanced our archaeological investigations into the realm of volume, such applications are being developed for our pilot projects dealing with biological cells and may be readily incorporated into archaeological research at a later time.

Extracting point features: corner points

Using the chain codes and NURB curves described earlier, we can extract profile curves on ceramic vessels (Razdan et al 2001). These profile curves have a number of points of interest to archaeologists such as corner points. Corner points can be described as an abrupt change in the orientation of a vessel wall, or a distinct angle in the joining of vessel parts such as the neck and body. For the automatic extraction of such points on a profile curve there is a need to adequately describe this feature mathematically. Hence, corner points are points of maximum curvature change on a profile curve and are extracted by comparing curvature values for all points on the profile curve. Comparison of the corner points identified mathematically (Figure 10) correspond very well with the locations of these points as identified visually by archaeologists.

Extracting curve features: profile curves

The profile curves contain various other sources of valuable information . One may be interested in the symmetry between left and right side of the vessel wall of the profile curve. This information is extracted into a signed curvature plot (Figure 11) and provides a valuable tool for the evaluation of vessel symmetry (Bae 1999). Further, we can generate an ideal model from the profile curve and evaluate how the real pot deviates from this model. These elements can provide information on the production of ceramic vessels and quantify the degrees of standardization within vessel classes. Finally, it should be stressed that although cutting planes to extract 2D information from a 3D model have here been applied to vessels only, the same procedure can be readily used to extract cross sections of bones.

Extracting surface features: facets on stone artifacts

A third and final level of feature extraction treated in this paper deals with surfaces. Surfaces form one of our major emphases as they allow us to retrieve 3D information rather than reducing a 3D phenomenon to 2D information. To extract surface information, the complete object has to be segmented into archaeologically and geometrically meaningful surfaces (Figure 12). Examples are the different facets on a lithic artifact such as the ventral surface, the partial dorsal surfaces, and the heel. These form the building blocks in any effort to refit these rocks into a complex 3D jigsaw puzzle.

Segmentation refers to the problem of extracting features or regions of interest from surfaces. Archaeologists observe and define features typically using subjective morphological definitions with implicit mathematical ramifications. The challenge, as in the corner point example is to make the criterion explicit. For example, ridges of high curvature bound facets of lithic artifacts.

Our first progress on segmentation applies to triangular mesh surfaces. Working with Anshuman Razdan and Gerald Farin, Sandeep Pulla used absolute curvature estimates along with the basic principles of a watershed algorithm (Mangan & Whitaker 1999; Pulla 2001; Pulla et al nd) to identify regions of interest and similarity on the surfaces of bones, lithics and pots. The problem of segmenting features, however, is not easily resolved. Often the definition of "meaningful" regions is application dependent, user dependent, or both. Owing to such dependency, decisions in segmentation are often ambiguous. We have, therefore, sought a solution that is unambiguous and consistent by way of its mathematical basis. "The key is to find the natural segmentation of a surface, rather than that forced by an arbitrary approximating scheme" (Fan et al 1987). However, fully automated segmentation is far from satisfying in many realistic situations. Some tweaking of internal methods and various tolerance values is therefore allowed in order to generate results that "best" suit a user's needs. (Pulla 2001)

Based on the idea of a watershed as used in geography, in which a watershed forms the dividing line between drainage basins, the computerized watershed segmentation scheme defines minima to which water would flow from the peaks surrounding that minima. By contrast to geography where this principle uses elevation in relation to neighboring areas as the defining characteristic for subdivision, this application uses absolute curvature allowing the recognition of peaks as well as valleys as the separating lines between watersheds (Figure 13). It was found that absolute curvature aided by smoothing equations yield superior results to Gaussian curvature. Applications of this method are particularly useful in segmenting facets on a lithic artifact (Figure 12). These regions in turn form the basis for the search for matches between stone artifacts.

The first step in the segmentation process is the computation and storage of curvature at each vertex or data point in the original point cloud. The curvature calculation for each point is based on a patch of nine or more points, around a particular vertex and the vertex itself (Pulla 2001). Next, absolute curvature minima are selected and form the "sink-holes" for the individual regions. Subsequently, vertices are assigned to a specific minimum by determining the way the imaginary water would travel (down the steepest drop in absolute curvature in this case). The initial regions are typically too numerous to be useful. Therefore, we increase the "watershed depth" to merge adjacent similar regions (Figure 14). Making the action of determining the watershed depth user defined we ensure flexibility to meet individual research needs. While significant depths that allow for the recognition of flake scars are typically found at similar watershed depths, these depths tend to be different for other application such as recognizing the joint surfaces on bones or the parts of a pot such as its neck, body, and base (Figure 15).

Data Storage

Having extracted a series of defining features from archaeological data, the next step is to organize the information to facilitate storage, query, and interaction with this information (Rowe 2001; Razdan et al 2001). An archiving and indexing system was developed and maintained to accurately describe and consistently search and retrieve shape data. Initial efforts to develop general index categories and feature descriptors are based on data from the pilot projects. While the data storage and query steps are similar across pilot projects, there are application specific differences across the pilot projects. Success will require reliable feature extraction, descriptions of features, shape algebra transformations, and indexing using an Object Data Base Management System (ODBMS).

To provide efficient access to text, volume, and surface information the project team developed a detailed and consistent strategy to catalog and organize the data. Significant research effort was devoted to identify and build upon the descriptive and cataloging standards that have traditionally been used to describe artifacts and on emerging metadata standards. For example, for the ceramic vessels, standards were adapted to describe surface models and derived mathematical descriptive data were analyzed to develop a vocabulary for the mapping of shapes, transition points, and critical data elements to identify and describe the vessels by shape and feature (Figure 16).

XML (eXtensible Markup Language) schemas were developed to provide a structure to organize, catalog, and describe the data elements. These schemas include application specific categories and are organized to differentiate general information (eg provenience, time period) and 2D information (eg vessel height, blade length) from 3D information. The 3D information data structures at the top level house the original binary data files, modeled files, and archaeological features. One level down the hierarchy, cognitive pattern primitives (CPPs) store the basic shape data that form the building blocks out of which meaningful archaeological features are constructed. The goal is to use the shape grammar and shape algebra to provide a natural language syntax to write a shape as a construct of tokens (CPPs) and combination rules. To link this spatial, modeled, and constructed data to descriptive data in existing databases, the schema provides a master identification number for use as the key to link data elements for a given artifact. This model is consistent with Dublin Core cataloging structures and emerging data standards within the discipline. This design permits the query engine to link to additional databases by developing an XML schema to map appropriate data fields between the databases such as a master ID#. Ideally, this process will become simpler as standards are developed for data definition and database design. In the meantime, this technique is scalable and provides the capability to add additional datasets to the query process as a proof of concept.

Query

A final element common to the three pilot projects is the query of information. We address the development of the interface, which is a Graphic User Interface (GUI), and the query process itself. The query provides access to a broad range of application specific features and allows the individual researcher the freedom to extract whatever data is relevant to his or her study. The first query interface developed by the project team supports interaction with the ceramic vessel data. Interaction with the bone surface data will be similar to the ceramic data and the capabilities of this interface will grow to incorporate differences and add appropriate tools for interaction. The lithic component addresses a much more complex interaction and will add pattern matching and fitting to the palette of tools available to researchers.

The Visual Query Interface

The visual query system 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 interactive surface and volume visualization capabilities and quantification tools to extract curvature, volume, scale, and linear dimensions for each data set.

The query process combines researcher input via a sketch-based interface with the ability to search by traditional text and metric data. For example, representative vessel shapes can be selected and modified from the supplied palette or a freeform profile sketch can be drawn in the interface window. Input fields for text and numeric fields support parallel query of descriptive and derived data within the databases.

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 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. Web designers, archaeologists, and general users are currently evaluating the prototype interface design. As additional models, such as lithic and bone data become available, the interface and related tool sets and capabilities will continue to evolve.

The query process

Behind the interface is a process that extracts key elements (features defined by the CPPs) and manages submission of the queries to the related databases (Figure 17). After the search information has been entered and the query is submitted to the server, a Java program extracts features from the sketch. A CGI (Common Gateway Interface) 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 (Extensible Stylesheet Language) file. The XSL file returned to the user browser contains thumbnail images and descriptive data for the top five vessels in the search results. The XSL file provides the data needed to view detailed information for any of the five vessels without the need of further interaction between the server and a particular user's computer.

When the search results are returned from the server, the client browser extracts and displays thumbnail and summary data from the XSL file. This information is extracted and displayed on the initial search result screen. The user can then select one of the thumbnails from the display. This action prompts the browser client to extract and display a manipulative 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 currently exploring how to bookmark or store search results to create a traceable research trail over time or multiple searches in a manner that are transportable by the user but does not require storage on the query server.

Discussion

We hope to have demonstrated that advancing archaeological analysis into the 3D domain can yield significant contributions to archaeology. While much of the research presented in this paper is ongoing and at an early stage of development, 3D data does permit us to attack a multitude of questions using a much refined means of analysis. Simple measurements on actual objects or images and drawings derived from these artifacts using calipers and/or rulers represent crude approximations at best and will not allow us to address issues such as vessel symmetry and uniformity adequately. Although advancing into the analysis of 3D digitized data can yield important contributions this move does not come without cost. Indeed, specialists outside archaeology are needed in the development of software and a distributed environment. This software and online interface development need to happen in close collaboration with archaeologists. Currently interdisciplinary research is a popular means of pooling resources and working toward similar ends, but the ability to work in a close collaboration with others outside of one's own discipline and reach an appreciable understanding of the knowledge and goals of co-collaborators from other disciplines poses serious challenges.

Additional costs such as the availability of technological equipment and artifact scanning time further limit the application of this type of research. It is for this reason that it is absolutely crucial that available information, software tools, and scan data are widely distributed. We are trying to achieve just that by making data available online for query and analysis. In doing so, much effort is going toward making the interface platform independent and data structures flexible to permit the addition of external data. It is also important that both raw and specialized data are available to allow researchers to tackle diverse sets of questions, rather than limiting the effort to questions deemed important by the archaeologists associated with a specific project.

While the costs are substantial, they are far outweighed by the potential advances that may be gained from this kind of research. This is particularly true when we consider that future advances in technology will ever expand research possibilities. Further, digital data will make it possible to preserve vulnerable information long term. This can be illustrated by the fact that numerous collections of human bones, ceramic vessels, and other Native American artifacts are often required to be returned to Native American tribes for reburial under the provisions of the Native American Graves Protection and Repatriation Act (NAGPRA). Digitally preserving these artifacts allow us to store and study this material long after its reburial. Further this type of data prevents the need to excessively handle fragile remains and facilitates the study of diverse sets of collections without continuously having to travel from museum to museum to study scattered bits of relevant material.

Conclusion

The interdisciplinary 3DK project at ASU provides ways to bring 3D research in archaeology into a new realm of analysis. By studying digital models of artifacts and bones acquired with recently developed and improved laser scanning technology and integrating the research with current problem sets in numerous disciplines, such as computer science, engineering, and information technology, truly interdisciplinary research beneficial to all disciplines involved becomes possible. Further, making the raw data as well as the developed research tools available online for query and analysis allows researchers from around the world to assess findings and conduct additional or alternative research on the artifacts. With the advent of rapidly developing technology and the broadened use of the World Wide Web, these steps appear as a logical stage of development in archaeology.

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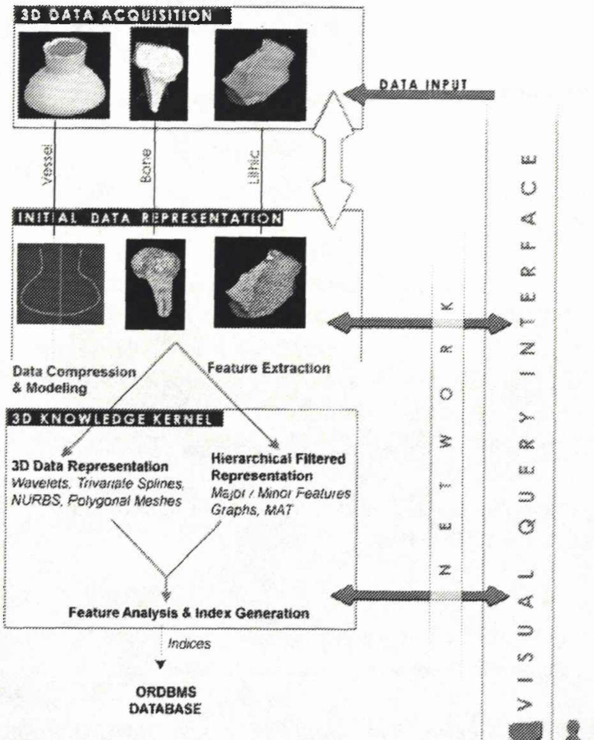

Figure 1: Data flow, knowledge abstraction and query in the 3DK project.

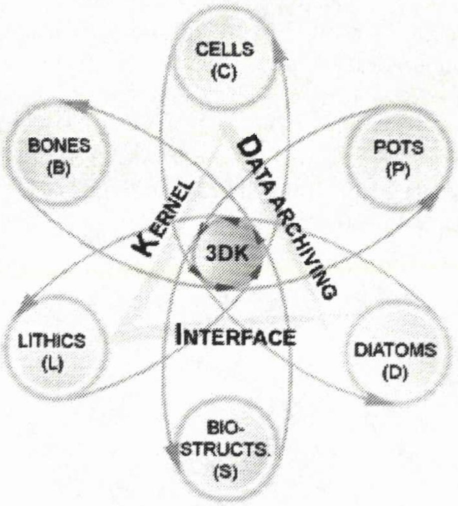

Figure 2: Pilot projects of the 3DK project and their relation.

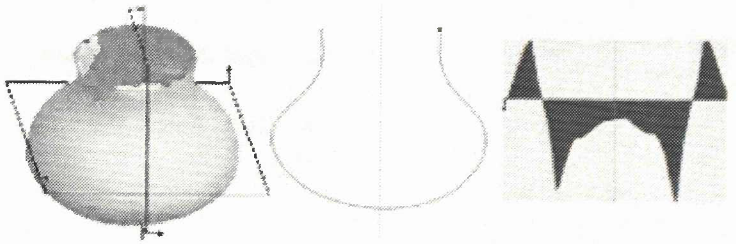

Figure 3: Views from the 3D interface developed for feature identification and profile graphing of prehistoric ceramic vessels.

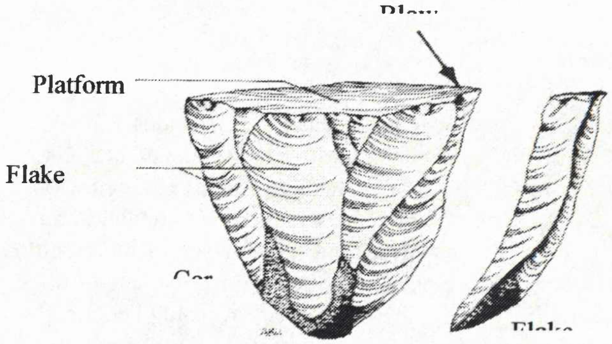

Figure 4: A flake detached from its core (Whitaker 1994)

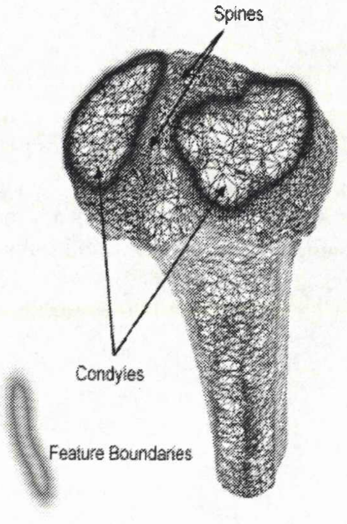

Figure 5: 3D scan of a human tibia illustrating the proximal articular surface for the knee joint, feature boundaries are outlined.

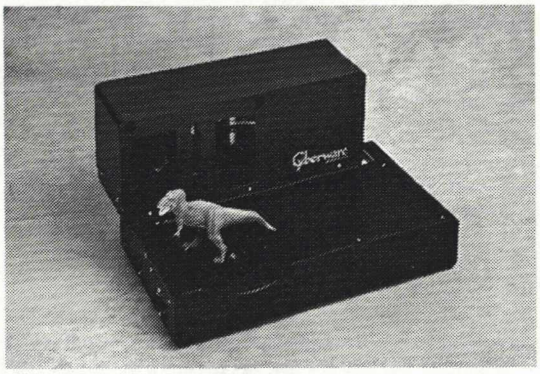

Figure 6: The small M15 Cyberware scanner. The width is about 75 cm.

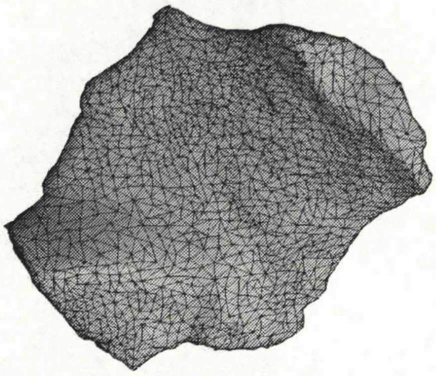

Figure 7: A triangulated, highly decimated point cloud data set representing the ventral surface of a stone flake.

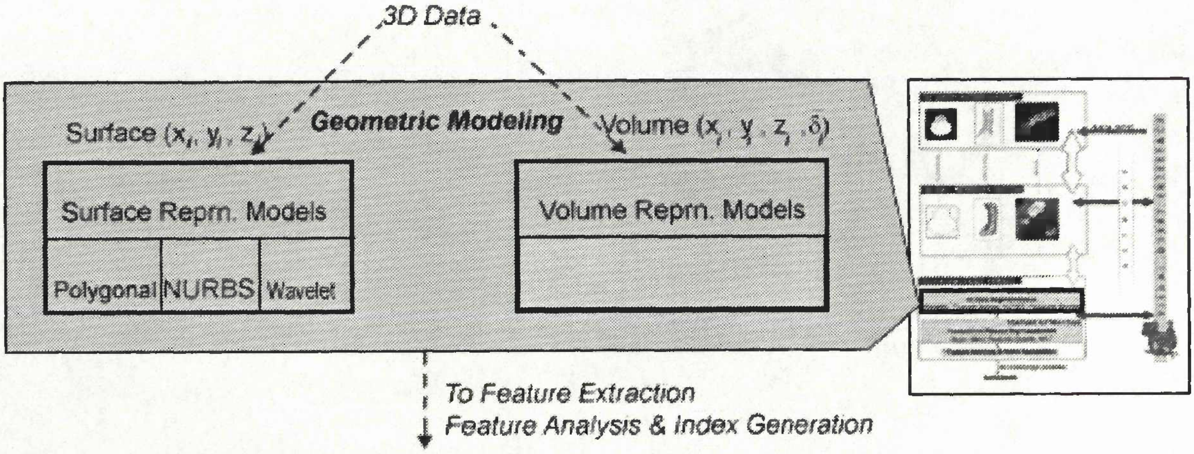

Figure 8: The Geometric Modeling module of the Kernel

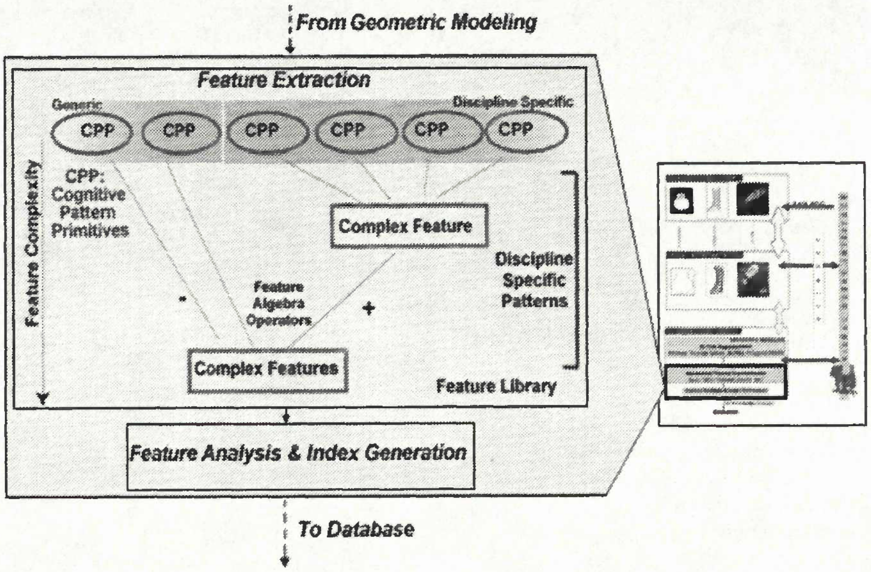

Figure 9: The Feature Extraction, Analysis and Index Generation module of the Kernel

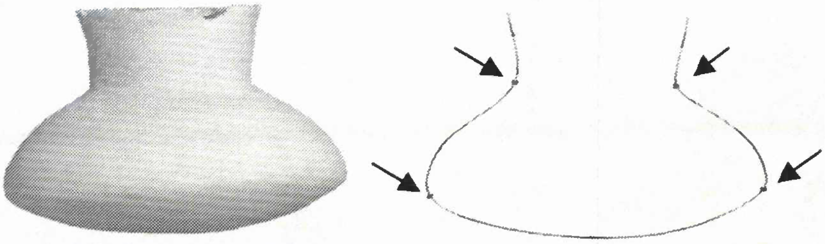

Figure 10: Original digitized pot (left) and the derived profile curve and corner points indicated by arrows on the right.

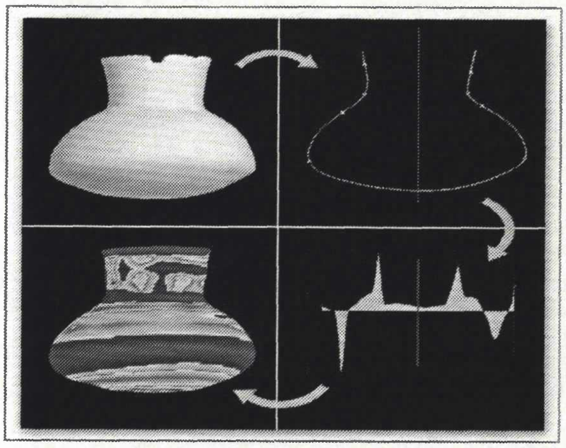

Figure 11: A Ceramic vessel, its profile curve and curvature plots reflecting the skill level of the vessel maker.

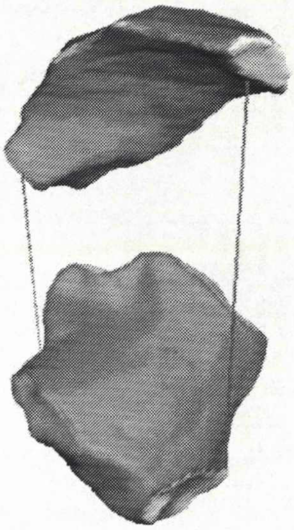

Figure 12: A fitting core and flake, each segmented using the watershed algorithm

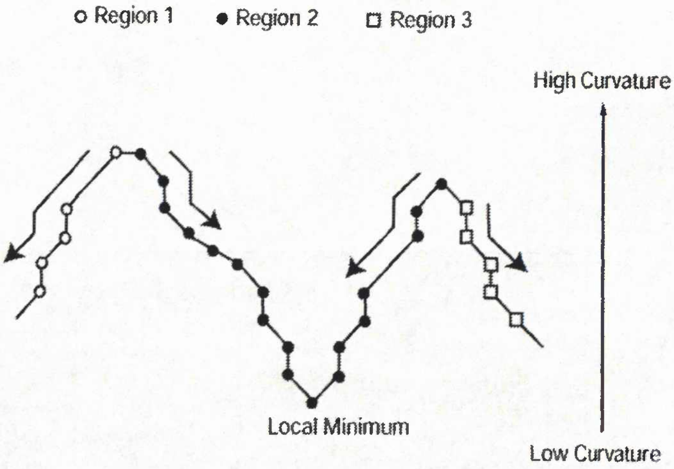

Figure 13: Curvature based segmentation

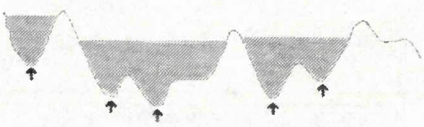

Figure 14: Merging similar regions by increasing the water depth.

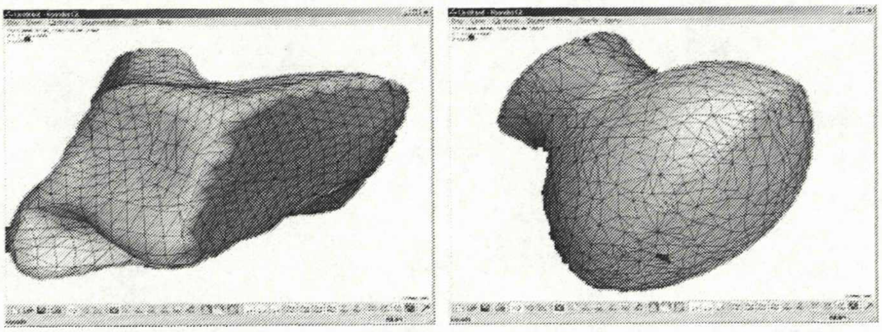

Figure 15: Triangulated surface meshes from a bone (left) and pot (right), segmented using the watershed algorithm based on absolute curvature.

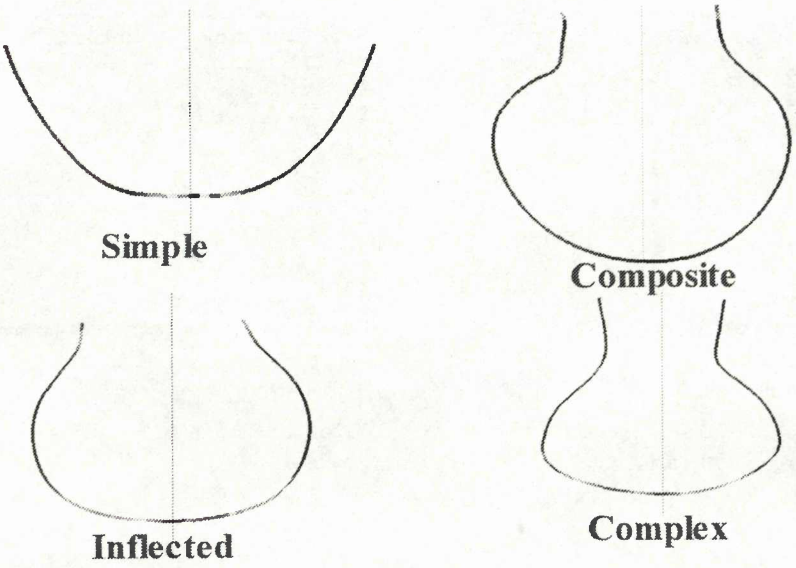

Figure 16: Types of base shapes for vessels.

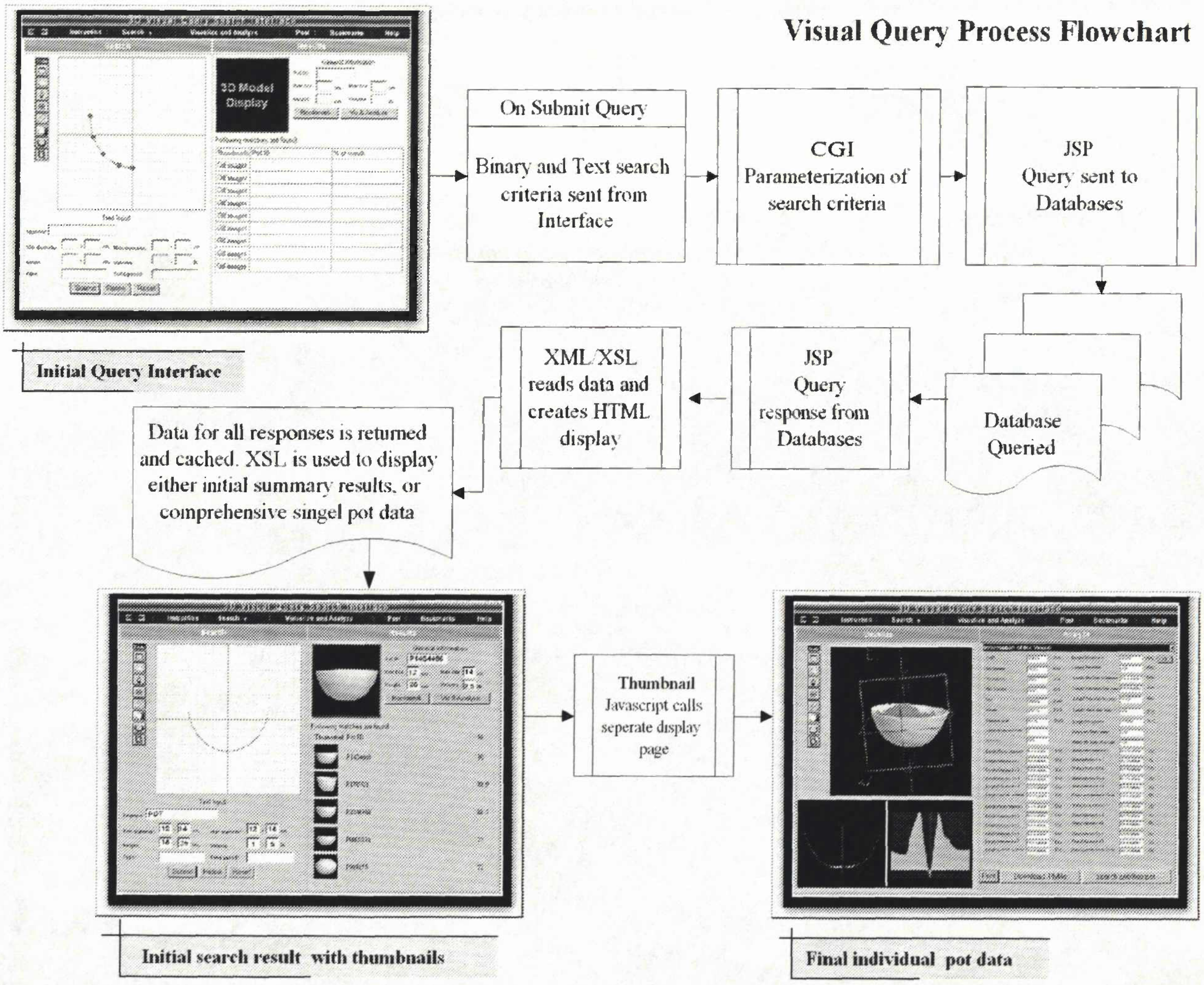

Figure 17: Figure showing the data flow in the 3DK Visual Query Process