Acquisition, Representation, Query and Analysis of Spatial Data: A Demonstration 3D Digital Library

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ABSTRACT
The increasing power of techniques to model complex geometry and extract meaning from 3D information create complex data that must be described, stored, and displayed to be useful to researchers. Responding to the limitations of two-dimensional (2D) data representations perceived by discipline scientists, the Partnership for Research in Spatial Modeling (PRISM) project at Arizona State University (ASU) developed modeling and analytic tools that raise the level of abstraction and add semantic value to 3D data. The goals are to improve scientific communication, and to assist in generating new knowledge, particularly for natural objects whose asymmetry limit study using 2D representations. The tools simplify analysis of surface and volume using curvature and topology to help researchers understand and interact with 3D data. The tools produced automatically extract information about features and regions of interest to researchers, calculate quantifiable, replicable metric data, and generate metadata about the object being studied. To help researchers interact with the information, the project developed prototype interactive, sketch-based interfaces that permit researchers to remotely search, identify and interact with the detailed, highly accurate 3D models of the objects. The results support comparative analysis of contextual and spatial information, and extend research about asymmetric man-made and natural objects.

Categories and Subject Descriptors
H.3.7 Digital Libraries – Collections, Standards, Systems Issues

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Keywords
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1. INTRODUCTION
The increasing power of computing, techniques to model complex geometry and compare to identify similarities has created powerful new capabilities to analyze and interact with data representing three-dimensional (3D) objects. The techniques to model and extract meaning from 3D information create complex data that must be described, stored, and displayed to be useful to researchers. Responding to the limitations of two-dimensional (2D) data representations perceived by affiliated discipline scientists, the Partnership for Research in Spatial Modeling (PRISM) project at Arizona State University (ASU) developed modeling and analytic tools that raise the level of abstraction and add semantic value to 3D data. The goals have been to improve scientific communication, and to assist in generating new knowledge, particularly for natural objects whose asymmetry limit study using 2D representations. The tools simplify analysis of surface and volume using curvature and topology to help researchers understand and interact with 3D data. The tools produced automatically extract information about features and regions of interest to researchers, calculate quantifiable, replicable metric data, and generate metadata about the object being studied. To make this information useful to researchers, the project developed prototype interactive, sketch-based interfaces that permit researchers to remotely search, identify and interact with the detailed, highly accurate 3D models of the objects. The results support comparative analysis of contextual and spatial information, and extend research about asymmetric man-made and natural objects.

2. Background and Purpose
Digital libraries are in the midst of a rapid and significant evolution. In less than two decades, the scope and complexity of digital collections have blossomed from the CR-ROM and videodiscs of the first American Memory project to the myriad offerings available via the Internet.

Similarly, scientific tools have evolved dramatically from observation, two-dimensional measurements, and statistical computation to include complex three-dimensional models and visualizations even in traditionally low technology disciplines such as anthropology.

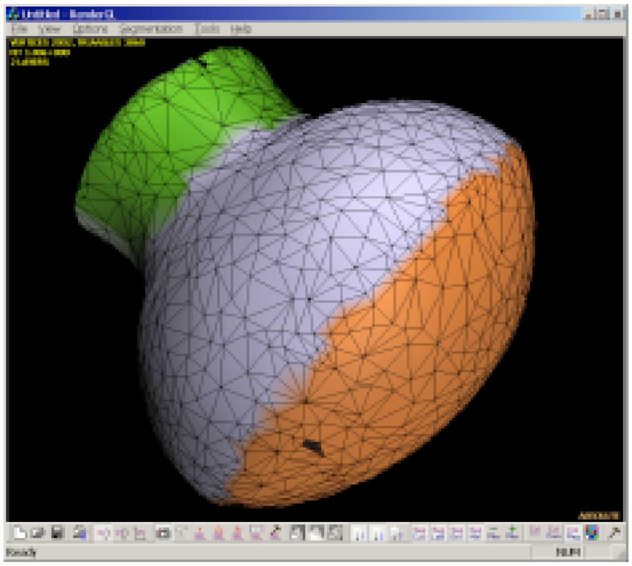

Figure 1. 3D model of Hohokam ceramic vessel.

Digital libraries today offer text, graphics, images and increasingly video, sound, animation, and sophisticated visual displays. Some now display three-dimensional objects, and permit the user to rotate and view an image of the original object in their browser window using QuickTime, plug-ins, or custom applications. A few examples include:

- -Forma Urbis Romae project at Stanford (PHP, MySQL and QSplat 3D viewer)
- -University of Texas Digimorph - CAT scan derived surface models of biological specimens displayed using QuickTime

This paper presents an overview of the development and application of powerful tools for geometric visualization and analysis used to create a 3D Digital library to capture, analyze, query, and display three-dimensional data by the Partnership for Research in Stereo Modeling (PRISM), an interdisciplinary research team at Arizona State University. Components of the processes include:

1. Metadata Schema and Organizational Structure
2. 3D data Acquisition - Scanning
3. Feature Extraction
4. Region Identification
5. Query Interface
6. Evaluation

As objects become more complex in terms of variety of shape and changes in curvature, it becomes more difficult to quantify and analyze. By developing mathematical techniques to represent the shape and curvature, accurate models of the surface of 3D objects such as ceramic vessels, bones, or lithics can be created. These surface models and sophisticated mathematical tools developed present the ability to analyze, identify, and compare the objects that they represent. The accuracy of the measurements derived from the 3D models created equal or exceed those possible using traditional 2D tools such as calipers and rulers. In addition, measurements such as height, width, maximum height or width, surface area, or volume can be easily, consistently and accurately calculated, even for asymmetric natural objects.

Use of 3D data also makes possible new measures based on topology and global or local changes in curvature that define the shape of the original object. The project built an interdisciplinary team of discipline and computer scientists, and technologists to guide an interactive development processes. The discipline scientists initially posed research questions, and then the computer scientists developed tools and spatial modeling techniques to address them. Using mathematical models and surface and volume information, many new and powerful analytic tools become available to spatially analyze objects. For example, boundaries between surfaces can be objectively identified, small local areas of changes in curvature identified and compared, and accurate, replicable measurements calculated automatically.

Once meaning has been linked to the changes in topology, shape, or curvature by the domain scientists a "feature" is defined. The modeling process provides an objective method to calculate physical measurements, and to identify boundaries and local areas of interest to researchers by the changes that are associated with the feature.

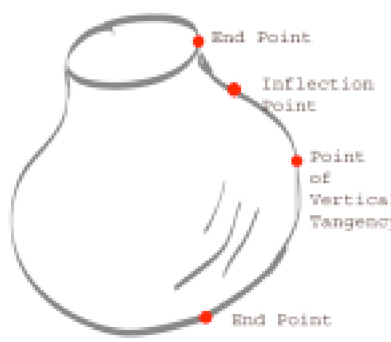

Figure 2. Components of interest for Ceramic Vessel

Once identified, each feature can be described by its size, position, shape or curvature. Examples of features that can be extracted from the model data include the maximum diameter or height of a ceramic vessel.

Features can also be components of interest to the researcher that are mathematically abstract, such as the base or neck of a vessel, keel of a ship, boundaries of the joint surfaces on a bone or spindles that form in the nucleus of a cell during meiosis. Often the tools developed to identify features and regions also provide additional capabilities that raise new research questions within the disciplines. These tools needed become new design challenges for the computer scientists, fostering a new cycle of tool development. For example, ceramic analysts have found tools that identify mathematically defined features found on the vertical profile curve of a vessel such as end points, points of vertical tangency, inflection points and corner points as features extremely helpful in analyzing vessel shape and style.

Figure 3. Laser scanning surface of ceramic vessel

In addition to the tangible research benefit the tools and techniques provide, a significant result of this process has been "cross-pollination" that has occurred as graduate students and faculty from different disciplines gravitate to a given project and explore application of tools and techniques to other discipline research.

A summary of data acquisition and analysis processes begins with initial laser scanning to acquire the 3D data that represents the object. Mathematical modeling is then applied to identify features and regions of interest to the domain scientists. Software tools developed by the project team generate analytic data about the original object, automatically assign metadata about spatial characteristics, and populate the database.

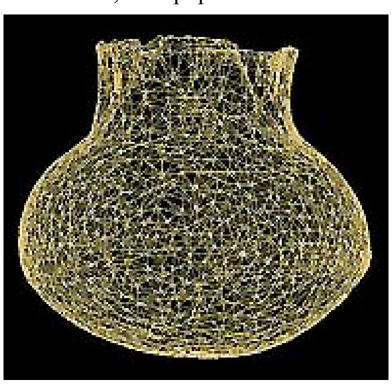

Figure 4. Point cloud of ceramic vessel combined from multiple scans.

A visual query process was developed to permit researchers to interact with the data using both contextual (text and numeric descriptive data) and spatial (shape and topological attribute) data. A sketch-based interface was developed that permits users to input both context and sketches to visually describe the object to initiate the search. Several text and spatial matching algorithms are used to identify and rank order objects within the database that math the search criteria.

Initial development of the digital collections focused on Classic Period (A. D. 1250 – 1450) prehistoric Hohokam ceramic vessels from central Arizona housed at the Archeological Research Institute at ASU. Additional development has involved bone shape and surface, lithic tools, brain structures and DNA structures in fertilized mouse egg cells. Research has extended to other disciplines with interest in spatial analysis including cloud formation, wind erosion, and facial recognition.

3. Methods

3.1 Metadata Schema and Organizational Structure

One of the greatest challenges in an interdisciplinary research effort is coordinating expectations among team members, and developing communication processes that bridge conceptual, strategic, and linguistic differences across the disciplines.

An iterative process was developed to share research questions, tools and intellectual approaches across disciplines at project meetings. The results were a gradual bonding of researchers, development of a shared vocabulary, and substantial interaction about potential research issues and approaches. These efforts provided a foundation for the initial modeling and analysis, and for developing the metadata structure needed to organize data for storage, analysis, and query.

A schema is an information class hierarchy that defines a shared vocabulary and a structure for documents described by that vocabulary. Use of a common schema for all project data regardless of location offers the potential to link and search across all of the databases that share the common schema. Dublin Core and Council for Preservation of Archeological Records (COPAR) metadata structures were used as foundations for schema development for this project. Extensible Markup Language (XML) tags were used to describe the contextual and spatial data elements, and for query and display of data.

A conceptual goal of the metadata component of the project was to develop an extensible schema structure that could accommodate adding new types of objects as the project continued to evolve. An object class was defined as the master class document type definition (DTD) for each item in the digital library database. For the 3DK digital library project, all of the additional descriptive data about each object was defined and organized as contextual or spatial classes.

Contextual types define text and metric information about the object. This context class includes subclasses for metadata associated with objects as they are acquired, processed, and archived such as type, item name, catalog number, collection, provenance, etc. At this phase of the project these fields were primarily determined by existing descriptive data elements, though efforts were made to design a schema structure that would accommodate adding new object types as necessary. To date, several iterations to refine the schema model to function effectively across object types have been completed.

Spatial data types define the 3D attributes of the object, including raw data, thumbnails, models, and calculated or derived data about the topology, shape, and composition of the object. Use of common descriptive components and geometric elements as new object types are added will permit shared use of the modeling and analysis tools across classes of objects. The project goal is to develop standards for description and organization that permit automated cataloging and population of data as objects are scanned and processed for entry into the database.

Due to familiarity and availability of resources, an SQL database was used to store the contextual and spatial data. Fields were assigned to each data element and large spatial data files were stored as hyperlinks. Generally accepted data formats such as binary, PLY, HTML, and XML have been used to make data accessible and simplify migration and access to the data over time.

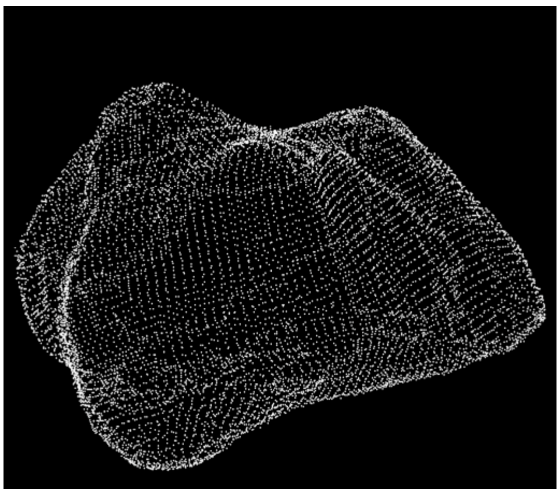

Figure 5. Point Cloud of scanned bone surface by Matt Tocheri.

3.2 Scanning and 3D Data Acquisition

Three-dimensional data about objects can be obtained from many sources. Laser scanners can capture surface data for 3D objects ranging in size from a few millimeters to large buildings and bridges. Scanning laser microscopes create three-dimensional data by stacking or "sandwiching" thin two-dimensional slices of data. CAT scanners and MRI also capture 2D images or "slices" of a 3D object. Each of these devices has the capacity to capture internal data about the objects in addition to the surface outline in each slice. The 2D image slices can be stacked to assemble a 3D volumetric model of the object. These techniques are used to create three-dimensional models of objects such as human bodies, artifacts, and manufactured objects. Improvements in the resolution, portability, and cost are making three-dimensional data capture devices and the data that they produce obtainable by many researchers.

The PRISM Digital Library project uses two Cyberware scanners, the M15 and 3030 to scan ceramic vessels, bones, and other objects up to roughly a 30" maximum dimension. The object is scanned by a laser, which captures spatial data (x, y, z) values for each point. The object is then rotated, and scanned again to capture additional data. This process is repeated until sufficient scans are obtained to combine to create a point cloud model to document the surface.

The Model 15 laser digitizer captures surface data points less than 300 microns (0.3mm) apart, producing high-density triangular meshes with an average resolution of over 1000 points per cm2. The digitized data generated by the scanner is composed of thousands of (x, y, z) coordinates that describe a point cloud that represents the surface of the object scanned. Further analysis requires generating a surface model from the point cloud.

The simplest method to generate a surface that approximates the original smooth continuous object from the thousands of points collected during scanning is to join adjacent data points to form a triangle mesh. The triangle mesh models the object surface, describing the 3D object with both geometry and topology (Hamann et al., 97; Amreshet al, 2002). The geometry describes how the various points are distributed in space while the topology describes the relationships between the points as they are connected in space to form the surface. IT is possible to take several snap shots around the object and "stitch" them together to create a displayable object using techniques such as QuickTime (QTVR). However, the QTVR representation is only a collection of 2D images, which can be presented to emulate a 3D view, and permit user controlled zoom or rotation of the display. Though the image appears to be 3D, there are significant differences between the QTVR display and an actual 3D representation of the object. The geometry and topology conveyed in a true 3D representation offer the capacity to derive measurements such as volume, surface area, diameters, height, or distances between points.

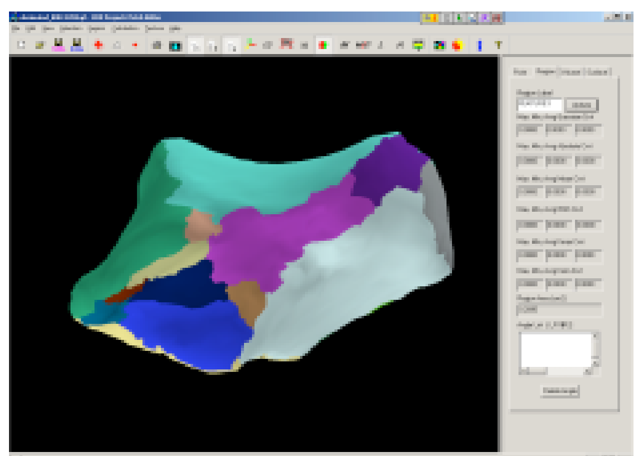

Figure 6. Region editor applied to trapezium data model by Matthew Tocheri

Modeling techniques are needed to create an actual measurable surface that represents the original object. In addition to the triangle meshes, PRISM software can represent these surfaces as Non-Uniform Rational B-spline (NURB) or subdivision surfaces (Bernadini et al., 98; Razdan et al., 98; Farin, 01, Farin, 02). NURB representation provides the capability to assess curvature distribution in complex objects such as identification of the joint surfaces from scanned data of a bone.

The accurate model of the object that results from this process provides the data and conceptual framework needed for objective, replicable analysis of surface and volume attributes of the objects under study.

3.3 Feature Extraction

Once the geometric structure has been obtained, the next step is to identify features and regions of interest to the discipline researchers. Ceramicists look for shape, symmetry, and curvature, cellular biologists look for structure of bio-molecular machines inside a cell, forensic anthropologists look at shape, and surface comparisons. A number of 3D modeling and analytic algorithms have been combined, and new techniques developed to segment the geometric structure into regions, and to identify meaningful features.

PRISM researchers developed a watershed-based hybrid feature extraction and segmentation scheme to work with the triangular meshes (Mangan and Whitaker, 1999; Pulla et al., 2002; Razdan and Bae, 2002). The algorithm automatically segments the surface into regions of similarity based on curvature. The areas identified can then be merged with adjacent similar regions, or split into smaller meaningful segments based on threshold values that have been defined by researchers. The nontrivial challenge has been to translate these aspects important to the discipline scientists into mathematically definable terms. For example, the transition between a vessel neck and body can be described mathematically as an inflection point, and the maximum width of a vessel by diameter.

Interaction within the project team has resulted in crosswalks of definitions that help translate terms and permit mapping mathematical concepts onto features meaningful to the discipline scientists. The use of 3D data permits accurate identification of maximum and minimum measurements and calculation of complex metric and descriptive data that are extremely difficult to obtain using 2D representations, linear measurements, and traditional measuring tools, particularly for naturally asymmetric or man made objects such as ceramics.

3.4 Region Identification

The second program developed is Region Editor that calculates more complex information about the object and its component features such as total object volume, absolute object symmetry, the area of surfaces identified, and the average angle at which surfaces intersect. Several of these measures are extremely difficult to determine accurately using traditional techniques, particularly for asymmetrical objects. The Region Editor also permits researchers to add contextual information such as technical data about the scan, image processing that has been used, provenance, or collection to the 3D data. The final action of the Region Editor is to create the metadata or XML file associated with the 3D data for archiving.

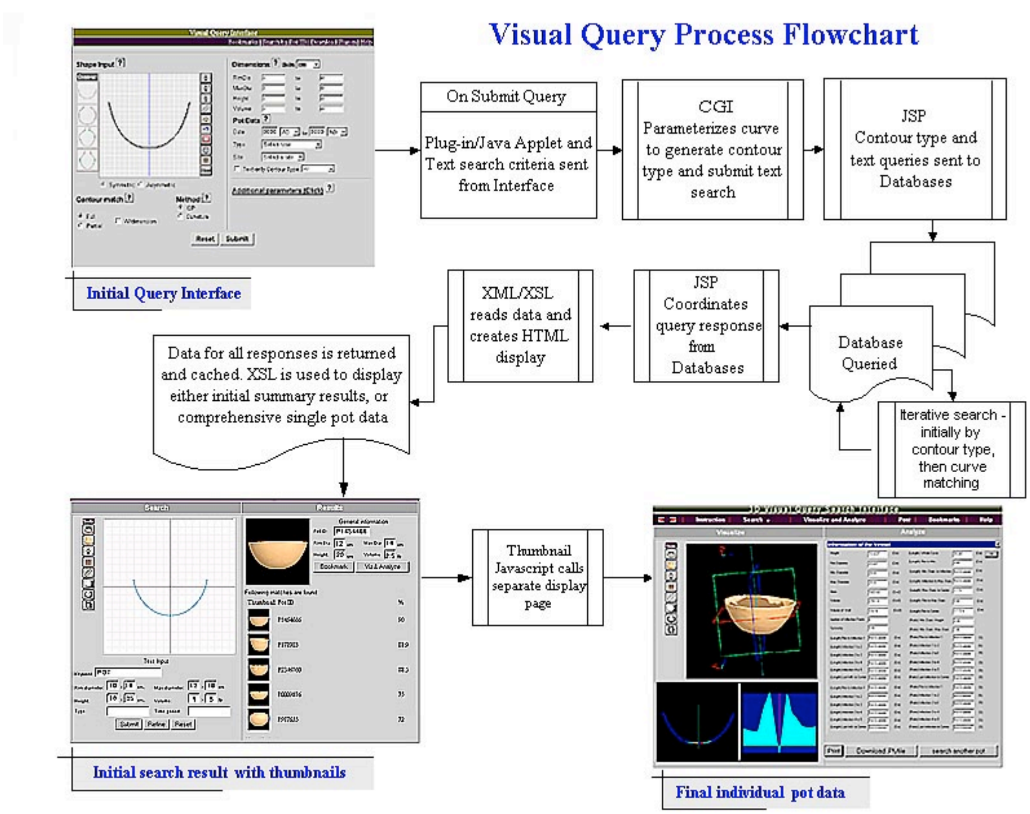

Figure 7. Diagram of Visual Query Interface and Search Process

3.5 Interface

From the perspective of interface, a primary design problem was how to accept input for both contextual and spatial searches. An interdisciplinary "visual query interface" team guided research into interface design, identification of desired capabilities, development of the interface, and ongoing revision based on evaluation data.

The PRISM team chose to design separate contextual and spatial input areas in the interface screen. Textual data was input or selected from pull down menus to query existing descriptive catalogs or databases. Search criteria include metadata such as name, type or number of the item, collection, or other catalog information about the object. This input area also permits the user to limit search by provenance by limiting the search to a specific collection, or by measurements such as height, width, or maximum or minimum diameter.

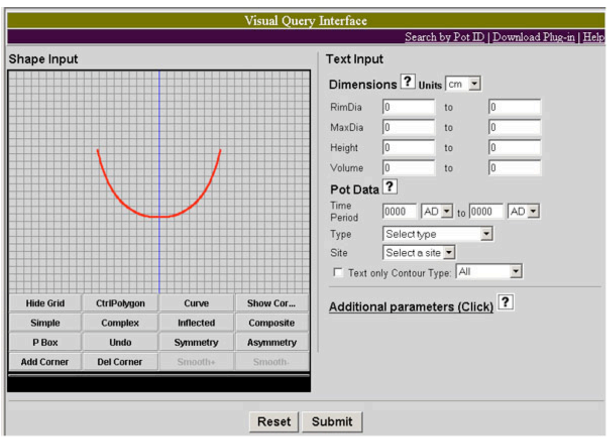

Figure 8. Prototype profile-based visual query interface for searching ceramic vessels

The most interesting interface design challenge was accommodating the input to query spatial data and to identify matching 3D shapes (Sakurai and Gossard, 88; Osada et al 2001, 2002; Razdan et al. 2001). To mirror the 2D profiles of the ceramic vessels familiar to anthropologists, the initial interface model used an interactive vessel profile to define the spatial search component. A gridded area presents a sample of a profile curve selected from the menu, or permits the researcher to draw a profile to be searched. Using the mouse and tool palette, the user can interactively create or manipulate the shape until it represents the desired vessel. Initially developed as a Netscape plug-in, the sketch interface has been converted into a Java applet to support multiple browsers and platforms.

After descriptive information about context and shape has been entered, the query is submitted. The descriptive and spatial information are separated and the multiple database queries are coordinated by project software. The contextual component of the query is handled as a conventional text and numeric database search. The spatial search uses a variety of size, shape, and curve matching algorithms developed by the project team to identify and locate similarities within the databases.

During search and analysis of potential matches, intelligent filtering techniques are used limit the search pool. Initially simple text, metric, or gross spatial classification criteria are used to identify possible matches from the database and reduce the search domain. As the search progresses, increasingly more complex algorithms are applied to the shrinking pool of potential matches. The goal is to minimize computational load and search time while accurately identifying all objects that match the search criteria.

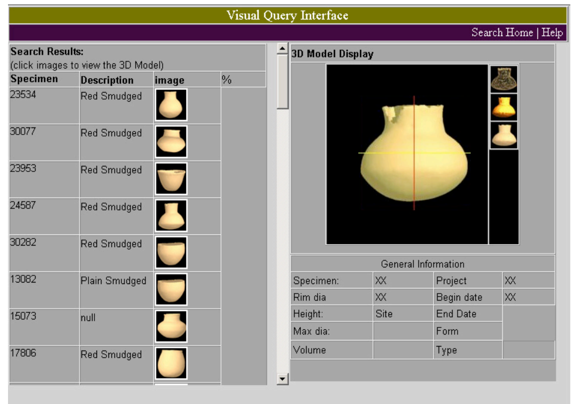

Figure 9. Interface screen with ranked search results.

Another algorithm ranks the query results by descriptive and spatial similarity to the query image. Query response information is presented sequentially over several screens, each providing an additional level of information about the selected objects. The first screen displays thumbnail images and brief descriptions of the top search results. Also presented is a large 3D display of the top search result, along with more detailed descriptive and calculated information. The 3D model can be displayed as a point cloud, wire frame, or full shaded surface representation at the discretion of the researcher. Using the mouse, the model can be rotated and viewed from any angle. Selecting a thumbnail of another search result from the cue of search results will replace its model in the 3D display window.

If more detailed descriptive information is desired, a third window that displays the 3D model, and two additional analytic tools - a profile curve and curvature plot, and additional descriptive data about the object. A fourth window can be selected to provide access to the complete descriptive and calculated data available.

Significant effort has been given to adapting the interface design to accommodate the differences in contextual data and analytic tools between different classes of objects. The object type metadata can be used to select the customized search template with fields for the contextual and spatial data appropriate for the object.

The visual query interface team developed training materials to guide new users and evaluation instruments to obtain formative guidance from users.

3.6 Evaluation

Several techniques were used to evaluate and guide the development of the project. In addition to general meetings and team building activities, process mapping and interviews of project team members provided qualitative and quantitative input to help build communication among researchers in the team. This iterative process has extended throughout the project.

Initial evaluation input regarding interface components and design were obtained from the roughly 25 project team members. The current version of the interface was used and assessed by the entire group at general and visual query interface team meetings throughout its development. The designs were critiqued, limitations identified, additional capabilities desired described, development challenges identified, and component work delegated to project teams.

Several evaluation sessions were held to obtain input from faculty and student researchers outside of the team. After initial orientation, research problems were posed to the evaluation groups, and users used the interface to locate individual target objects by context, shape or size. Users were encouraged to explore the 150 ceramic vessels in the test database and comment on the clarity, scope, and ease of use of the interface. A revision cycle followed each evaluation.

4. Findings

The spatial and volume modeling and analytic tools developed by the project team permit discipline researchers to quantify and accurately replicate measurements of complex 3D objects. The feature and region recognition capabilities assist in visualizing complex, abstract concepts of interests to discipline researchers.

The iterative design process and team interaction evolved and worked well, particularly as the project scope and development focused in the second year of the project. The regular interdisciplinary interaction among the faculty and students was essential in developing comprehensive metadata schema, and provided positive, constant pressure to extend the project design requirements.

The challenges involved in developing the conceptual models to extend textual and metric contextual data and develop metadata for surface modeling were significant, but were exceeded by those that arose as volume data was addressed. As the tools and techniques developed for volume data became available, several new capabilities became available to extend analysis of surface models. The growth of capabilities that resulted from this iterative process would have been virtually impossible in traditional research that focused on a single discipline.

The conceptual model developed to describe data using object class with subordinate context and spatial characteristics worked well to guide development of both analytic tools, and the query interface. The ability for users to simultaneously query by context and shape was essential, and provided significant challenges for both computer scientists and interface designers. Initial development of the sketch-based 2D profile model for the spatial query laid the foundation for the even more complex development of the full 3D input modeling for query input that is currently underway.

The capabilities and standards of virtually every technological component of the project were in flux during the course of the project. A few examples include:

- -Portable scanners evolved considerably in terms of accuracy, rivaling the larger fixed scanners by the midpoint of the project.
- -Metadata and XML capabilities and standards were evolving dramatically. Schema development tools and strategies became more powerful.
- -Initial SQL search capabilities began to be augmented by SOAP and XML search capabilities.
- -The reliability of distributed servers, databases, and networked access tools has evolved significantly since the start of the project.
- -Java development permitted replacement of Netscape plug-ins to simplify configuration and ease cross platform access, and evolution of Java 3D has provided significant new opportunities for development of a full 3D query interface.

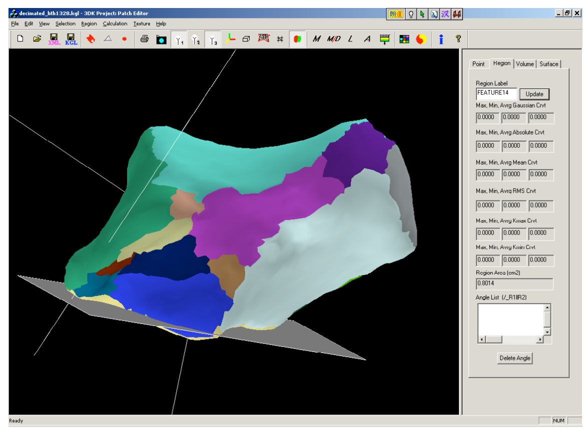

Figure 10. Prototype bone joint surface tool interface by Matt Tocheri

5. Discussion

One of the pleasant surprises during this project has been the ease of extending the modeling and analytic tools developed for one specific discipline to other research domains and the interactive growth of the tools for surface and volume modeling and analysis. The improvements that have resulted from the iterative process of identifying a domain research question, developing an application tool, deployment, analysis of potential applications across other research domains, and identification of new research questions has generated significant process in developing modeling and analytic tools applicable to 3D data.

As 3D data acquisition tools become more affordable and readily available, the amount of 3D data that must be described, stored and displayed will grow dramatically. Accommodating this huge data management challenge will require development of standards and tools to begin to analyze and add meaning to the data.

Several efforts are underway by the PRISM team, or are planned to further extend the capabilities of the tools developed, and their application to domain research. In terms of infrastructure, the move from custom plug-ins to Java will simplify deployment.

We are exploring alternatives to the SQL database currently used, such as object-oriented databases. Another effort to improve searching is a pilot XML search protocol developed by the National Science Foundation Biological Databases and Informatics project at Arizona State University (BDI) research project in conjunction with the ASU Long Term Ecological Research (LTER) Metadata Committee and the Knowledge Network for Biocomplexity (KNB) Project at the National Center for Environmental Analysis and Synthesis (NCEAS). The "Xanthoria" metadata query system Developed by this project team uses SOAP (Simple Object Access Protocol) to send XML query requests and responses, and supports simultaneous web-based querying of distributed, structurally different metadata repositories.

The spatial analytic tools continue to develop as improvements are made in the feature extraction and region editing applications and more powerful techniques are developed compare curvature, identify matches and rank search results. Key to these efforts is the expanding partnerships with other research areas with their own unique modeling and visualization needs. Included to date are more complex anatomical data from CAT scanners and MRI, cloud formation pattern recognition, geological erosion, and identification of targets within complex, noisy environmental data.

Interface design continues to evolve. The project is evaluating models developed for 3D query and display by other projects including:

- -Princeton 3D Models Search Engine using Takeo Igarashi's Teddy 3D sketch interface
- -National Center for Biotechnology Information (NCBI) Cn3D Genetic viewer

The development of a realistic 3D interface models that permit the researcher to sculpt the query in 3D space is progressing, as are additional analytic tools such as planar overlays to visualize and objectively compare joint surfaces of bones. Techniques to bookmark searches to permit replication and simplify comparison of objects within the databases are also being explored. A complex variation of bookmarks involves providing a replicable trail for researchers using the region editor and additional analytic tools such as the planar overlay to interact with the data and create their own interpretive models. Creating storage techniques for these derived, researcher defined or modeled data, and managing "version control" to permit replication and deconstruction of the analysis is another challenge.

User evaluation of the current interface layout, color palette and design continues using both surface and volume model data. In addition to initially developing specific bone or ceramic vessel interfaces for the different research domains, the project is working to identify commonalities and conventions to develop a unified interface model. This common design appears to be possible in initial query interface screens, with differentiation of interface display occurring as objects are identified, search results are returned, and researchers drill down into object data that may vary across disciplines.

6. Conclusions

Development of the current model 3D digital library has been an interesting exercise in interdisciplinary project development. Translation between disciplines has taken time and effort. Even when common vocabulary is used, the discipline specific definitions and nuances can vary significantly.

The spatial modeling tools developed to identify features and extract regions of interest have proven valuable additions to research in the partnering disciplines. The initial challenges have focused on data acquisition, and development and display of models.

Initial digital library efforts to display images of surface models using QuickTime and plug-ins have significantly expanded research and science education as complex natural objects become approachable through such visualization. Adding modeling and analytic tools based on surface and volume that permit objective quantification and analysis of 3D data has the potential to further extend research in virtually every discipline studying 3D objects.

As 3D data and the tools for visualization and analysis become more available, there is an increasing need for intuitive interfaces to provide gateways to the data. Researchers bring different strategies and approaches, and learning styles differ widely across potential users of 3D data. Visual literacy and the sophistication of users also vary dramatically among users.

Standards are needed for data description, storage, interchange, and searching. Understanding of this complex multidimensional data will be essential as records managers begin to interact with collections of 3D data, and as it begins to reach archives. Conventions for display and organizing research tools are essential to effective preservation and access.

Evaluation and continued research into learning styles, communication preferences, and visual communication and display are needed to guide interface design. Clearly, development of simple, elegant, easy to use interfaces to accommodate the range of tools and user preferences for spatial data and modeling will be a significant challenge now and in the future.

7. Acknowledgements

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