The 3D Colonial Philadelphia Project - Digital Restoration of Thin-shell Objects for Historical Archaeological Artifact Analysis and Interpretation

Introduction

Historical Archaeology, the scientific study of recent human history, is dependent upon extensive analysis of three-dimensional artifacts, namely the physical evidence left behind by people living in the past. One important category of artifact research – ceramics analysis – lends itself to the application of computational *vision enabling technology*. Ceramics are characterized by their thin nature: their shape is formed by a thin smooth surface rather than a solid volume. In the vernacular of computational language, these types of vessels are categorized as "thin-shell" objects. We adopt this terminology in referring to these types of artifacts for this proposal.

British export ceramics (BEC) are the class of ceramics selected for use in this study. BEC are the first factory made, mass-produced, goods available worldwide via global colonial trade. Beyond the realm of manufacturer trade and global marketing, BEC become part of colonial peoples' lives through their use in the foodways behavioral complex (the preparation, presentation, and consumption of food). Strongly bound to cultural traditions, this range of human behavior is resistant to change making it – through its physical residues – particularly useful for the study of culture, culture change, and cultures in contact. Material culture residues of foodways are directly pertinent to the study of early market economics, social and economic scaling in colonial society, and ethic and social identity making and marking in the development of the modern world.

When recovered from an excavation context, BEC, like all ceramic finds, are fragmentary and often exhibit missing pieces. Before analysis for meaningful history interpretation can proceed, vessels need to be reconstructed and identified as to shape (hollow or flat form) and functional category (pitcher, cup, bowl, etc.). This process of "mending" thin-shell artifacts is time consuming and often bottlenecks further study and analysis. The objective of this proposal is to develop novel computer vision technology that will assist the ceramic artifact reconstruction process -- if not fully automate it -- thus enabling timely analysis, interpretation, and presentation of archaeological findings. Such novel computer vision methods integrated with archaeological evidence and expert knowledge would push forward the state-of-art in computer science for reconstructing and modeling thin-shell structures and transform Historical Archaeology laboratory practice through:

- More efficient and proficient laboratory processing of ceramic vessels;
- Financial and human resource savings (i.e., time and money);
- Faster advancement to the analysis phase of research (analysis follows identification);
- Enhanced tools for management of artifact collections in artifact repositories;
- Expanded capacities for collections reuse - remote research capabilities via digital proxies;
- New optimized possibilities for digitized artifacts in public interpretation.

This project is unique in many ways. It will draw upon the ceramic assemblage recovered during recent historical archaeological research on the Mall in Independence National Historical Park, Philadelphia, a project that has been described as the best preserved and most richly diverse American urban colonial archaeological landscape ever excavated (see Figure 1a). The site yielded more than one million artifacts dating from the late 17th to the mid 20th centuries including hundreds of thousands of thin-shell pieces making the site very suitable to the proposed study (see Figure 1b). We strongly believe that approaching this vast ceramic collection with novel theoretical and computational vision research technology and a strong collaborative methodology among the practitioners will have a profound impact on the study of the past at this site and will transform Historical Archaeology laboratory practice around the world. The proposed project is deemed of great value and need by the U.S. Department of the Interior National Park Service, as evidenced by their letter of support (attached as a supplementary document) to our proposed work.

(a) (b) (c)

Figure 1: (a) Archaeologist excavates an 18th century privy deposit; (b) In the lab, an archaeologist works with thousands of ceramic shards; (c) Mending fragmented ceramic objects is a labor-intensive manual task.

Specific Aims

***Aim 1:* Digital Restoration of "Thin-Shell" Archaeological Artifacts**. In this proposal, we will derive a computational framework based on computer vision research that addresses the fundamental research problems underlying digitally reconstructing fragmented, thin-shell, ceramic artifacts. Reconstructing thin-shell vessels from their fragments pose significant challenges since the fragments can originate from different specimens whereby each fragment stands on its own; or whereby each fragment comes from an unknown source (object) and the fragments do not share any apparent geometric/photometric information. As depicted in Figure 2, we tackle this problem by exploiting local and global geometric and photometric information in the form of 3D surface properties, hypothetical shape models and geometric invariants, and colored decorative drawings and prints on the surface, as well as seamlessly integrated expert and domain knowledge to take full advantage of archaeological information to "guide" the reconstruction. This agile methodology (expert opinion applied in the process of product development) will be ethno-archaeology insights derived via observational study and informant interviews.

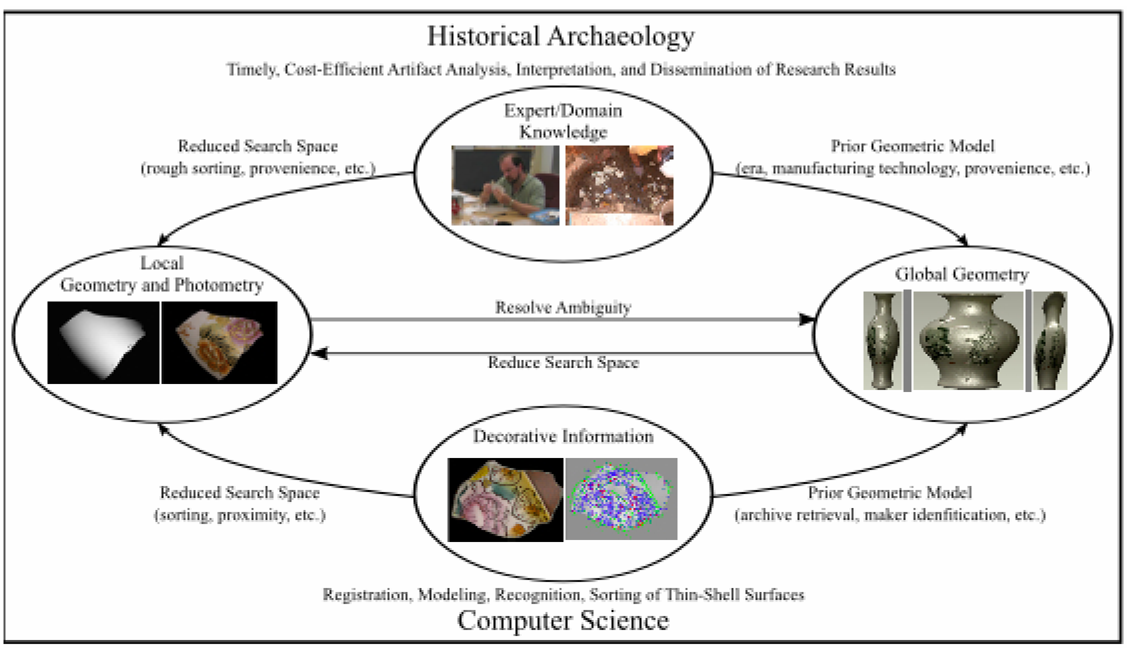

Figure 2 – Overall System

One key source of prior information is the provenience or context from which artifacts or pieces are tied together in accordance to the dig level. This helps in identifying the likely pieces that would be considered as likely candidates for mending. We will take pictures of the pieces during the dig and form a label level depository that will be accessed during the mending process. As depicted in Figure 2, this information will be particularly useful for narrowing down the possible neighboring fragments when putting together the fragments piece by piece. We propose formalizing the theoretical problems that are encountered in this archaeology methodology, specifically eliciting the cognitive typologies used and innate in the vessel mending and identification process. The archaeological contextual information inferred from the look (and even feel) of the fragments by archaeologists such as the possible time frame and specific manufacturing technology will help in establishing prior geometric models, such as a group of vessels of specific types of shapes, that can be used for identifying the fragment location on the original surface.

A comprehensive computational framework for virtual reconstruction will be created that is based on the geometric (global and local) and photometric (color) information relating to the excavated pieces. The global geometric information will be exploited using a novel shape invariant based on the intrinsic curve/surface geometry of the artifact fragments. The excavated fragments will be matched to a possible generic prior shape model by matching geometric invariance (with respect to the class of morphing transformations) computed on the fragment and the generic prior shape model. A strong point is that intrinsic surface properties or markings are usually not apparent to the naked eyes of the best of experts, and hence the technology will be an added tool for the mending process that would not be otherwise available. The local shape and color information of each fragment will be exploited by using a novel registration method based on the geometric and photometric surface continuity. It first matches contours of the fragments to identify potential candidate pieces that lie next to each other on the original surface and then computes the relative embedding of one fragment into another by minimizing a metric that evaluates the geometric and photometric continuity of the surface across the pieces. Finally, photometric information on the ceramic fragments, typically found as decoration and manufacturer or ‘maker’s marks’ (trademarks) will be exploited by computing a novel multi- scale representation of the appearance in the form of a deep-structure map. We will develop novel algorithms for partial matching of these maps that can deal with missing appearance information, deformation and color change. For archaeology’s needs, this will form a digitized, inter-active, reference database which can help reducing the search space of possible neighboring fragments for local reconstruction. We will also develop efficient indexing algorithms for retrieval of candidate models from large databases of prior models based on structural properties of appearance maps.

The main three research thrusts, namely the global matching, local registration, and photometric matching and indexing, together with the seamlessly integrated expert/domain knowledge complement each other leading to a comprehensive machinery for assisting, if not fully automating, virtual reconstruction of fragmented artifacts comprising thin-shell structures (again, please see Figure 2).

The development of each of the three components requires novel theoretical and computational investigation, which individually and collectively would push forward the state-of-art of vision technology. It also leads to a significant step towards digital virtual reconstruction of general fragmented thin-shell structures, a problem that remains open in Computer Science research. Once created, this vision technology is applicable to all other historical archaeology research be it university or museum-based or private sector research (environmental impact assessment studies). The technology’s development is especially relevant at this time because archaeological heritage is both increasingly popular and also increasingly endangered. Vision enabling technology can contribute in multiple ways to Heritage Tourism, of which archaeology sites are a part. Heritage Tourism is the largest and most financially productive sector of one of the biggest industries in the world – Tourism. Meanwhile, modernization and urban development is wiping out archaeological sites at an ever increasing rate. Vision enabling technology for ceramic vesselization would decrease human and funding costs associated with archaeological lab processing of historical ceramics freeing resources important for heritage tourism needs and site destruction mediation. At the same time, the reach of the research is expanded via new envisioning technology (digitized tools) useful for collections management (remote research by virtual proxy) and virtual public history interpretation. These research activities would have constant feedback from the Co-PI (Dr. Jeppson, the in-house archaeologist) that impact our stitching of the fragments, as well as in providing the appropriate data, as well as disseminating our findings.

Aim 2: **Educational Component and Broader Impact of Virtual Archaeology.** A key aspect of the project is to integrate the proposed research and education. This will be carried out via several routes. (1) Course development. The PIs plan to develop a new graduate-level course on Computation Methods in Digital Archaeology covering materials closely related to the project, in order to prepare and expose Drexel students to the state-of-art in archaeology, computer vision and geometry, computer graphics, and digital media. (2) Digital media research at Drexel. As the first ever digital archaeology research project hosted by three academic units at Drexel University, the project will promote computational and digital media research at Drexel. The proposed research and development are expected to produce several multi-disciplinary PhD dissertations, as well as provide projects for undergraduate and graduate students alike. (3) University-Government collaborations. The PIs plan to exploit the close connection with Department of Interior and to leverage the Drexel University co-operative education that will allow Drexel students to integrate with our collaborators at U.S. Department of Interior National Park Service, Independence National Historical Park. Another broader impact is to use virtual reality and augmented reality technology to educate large groups of individuals, such as for national park exhibits, to develop strategies for making new media resources available for education, tourism, and commerce. (4) High school education. The college of engineering at Drexel has been hosting high school students and teachers through the ten-week summer research REU and RET programs. As active participants in these programs, the PIs intend to host REU students to work on exciting projects related to our project, as well as hosting RET fellows that will work with the PIs to develop material that can be brought back to their own schools to introduce their students to computational and digital media research. The PIs will also give seminars to the at large RET and REU participants in order to attract the high school students to computational and digital media research.

Background and Significance

Drexel University has initiated “3D Colonial Philadelphia” a project with the aim of becoming a research and production center, as well as a repository and disseminator of information for the study and use of virtual technologies, artifacts and interactive environments dedicated to interpreting colonial and federalist eras of American history. Work has begun on the 3D modeling of significant historic structures at 5 sites located in Philadelphia and surrounding counties in Pennsylvania and New Jersey. The effort has already captured the attention of the local press as evidenced by a recent article (attached as a supplementary document). The application of Vision Technology research to 3D Colonial Philadelphia will dramatically advance our effort.

In regards to recovered artifacts from Independence National Historical Park, the first step of vessel mending and identification for this unprecedented collection, even with the assistance of an army of volunteers, is projected to take 15 years. Fortunately, the development of new research vision technology and tools can assist with the categorization and mending of Industrial Age, factory produced, ceramic vessels recovered in historical archaeology sites. Vision enabling technology for artifact vesselization would be a revolutionary breakthrough for historical archaeology in the same vein that Carbon-14 dating changed prehistory: It would provide a critically important baseline of definitive information necessary for subsequent pursuit of critical historical analysis. Pursuing such technology is a responsible strategy given that the discovery and stewardship of this vast artifact assemblage involves a federal government undertaking; the financial savings will be significant and the quicker access to the history information that results will be relevant for all.

Research Design and Methods

Aim 1:

In this section we present our proposed research methods in support of the fundamental research problem of developing a comprehensive computational framework that also leverages expert knowledge for digitally reconstructing fragmented thin-shell archaeological artifact. We discuss the methods used in our three main and complementary research thrusts, namely the global matching, local registration, and photometric matching and indexing, leading to a comprehensive machinery for assisting, if not fully automating, virtual reconstruction of fragmented thin-shell artifacts.

Generic Models, Decorative Information and the Expert Opinion

Ceramic production classifications researched in 18^{th} and 19^{th} century factory price lists, inventory lists, and bills of lading reveal period vessel types (the range of available ceramic forms or shapes – bowl or dish) and other standardized manufacturer specifications for these (vessel sizes and modes of decorative style production). These period ceramic typologies (originally relating to values of expended energy, talent, and cost in decoration) serve as the a priori knowledge needed for modeling vision enabling technology. This range of known and thus possible, expected, mass-produced BCE constitutes prior knowledge for the needs of computer modeling. The vision enabling technological system will use this a priori knowledge along with other expert opinion in assuming particular types of vessels as possible models when mending fragments: For individual recovered fragments, the exact shape of the vessel might not be identified at the outset; assumed knowledge of the vessel shape might be derivable from specific diagnostic features (e.g., footrings) but not necessarily the full range of markings (decoration). It is within this uncertainty space that the vision system will operate making use of prior information and expert opinion. The system should function when prior information is scarce or even unavailable. It is expected that the system will be able to realize new generic models (i.e., isolate and identify previously unknown ceramic vessels) that are exceptions to the a priori and expert knowledge and that can't be reached from the assumed and entertained morphing transformations. The spectrum of modeling includes two extreme scenarios, each with its own complexity: On one extreme, the system can have very few generic models but allow for complex morphing transformations that will take us from the generic to the encountered object. On the other extreme, we can have many more generic objects and simpler morphing transformations. Whereas the former will be used in the total or extremely limited case of expert opinion, the latter will rest on information gleaned from previous site excavations dating to the relevant period, from historical records, and from comparative museum collections, and finally from the provenience or the context from which artifacts or pieces are tied together in accordance to the dig level. Our proposed work will include a focus on the recognition of manufacturer marks (maker's marks or trademarks) for identifications and for delineating the entertained prior models (hence limiting the uncertainty and guess work in the computer aided stitching of fragments into meaningful objects). Beyond prior expertise gleaned from historical records left by ceramic manufacturers, ethno-archaeology research will be conducted for the development needs of the vision enabled technology. Ethnologic research on archaeologists mending ceramics will provide analogy for the computer modeling. In this manner, tacit diagnostics related to ceramic body texture, glaze, etc., learned during formal training and field experience will be identified through observation study and informant interviews.

Global Model and Intrinsic Geometry and Invariants

In this section we describe the methodology that we propose to solve the specific problem of piecing fragments or artifacts to a possible generic shape model identified by the expert. Uncertainty in the expert specification is accommodated by allowing the object to lie within the class of morphing transformations on the generic expert model. We will assume knowledge of the general class of transformations (for instance an affine, or cubic or 4^{th} order polynomial morphing map) but not of their specific values. We propose a method of partial alignment or registration that circumvents the need to know such values. It is based on the alignment of fiducial points on the fragment to their corresponding ones on the generic model. These fiducial points are local intrinsic points computed from the differential geometry of the surface [2] (e.g., maximal and minimal curvature points under similarity transformations [3]; or points of inflections, or zero torsion points [3] on parabolic curves [3] on the surface under affine transformations, etc. as shown in figure 3) and that remain intrinsic points under the morphing transformation. On a typical ceramic vase, there will be hundreds of such fiducial points, which can also be augmented by hundreds or even thousands of others if the sherd has markings on its surface.

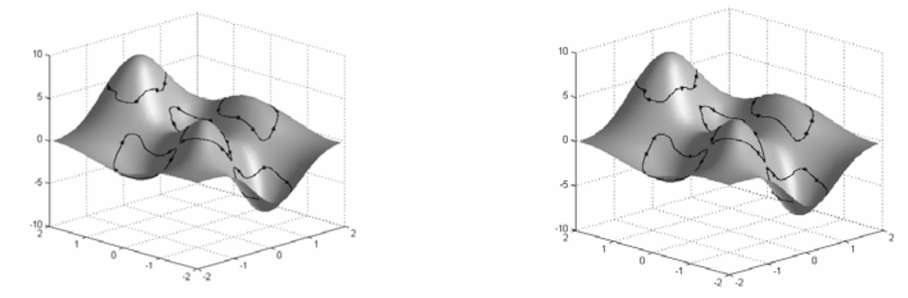

Figure 3: Fiducial points residing on parabolic contours of the surface
Left: Zero-volume (v_1) points. Right: Zero-torsion points

Those fiducial points residing on decorative patterns contours, in particular, could also be extremely useful for flat pieces where fiducial surface markings are rare or nonexistent. We will exploit both intrinsic curve and surface fiducial points to help in the mending process.

To locate the corresponding fiducial points in the absence of knowledge of the morphing parameter values, we propose to derive absolute invariants to the morphing transformations. Examples of absolute invariants are: the ratio of lengths between points in the presence of a similarity transformation; or ratio of volumes spanned by set of four intrinsic surface fiducial points under affine transformations; etc. To reduce the matching search we propose to order the invariant set so that the matching reduces to a simple string matching. This process is shown in Figure 4 for fragments that belong to a vase artifact that is seen as being generated by morphing a prior model (generic model) to the parent vase that the fragments have originated from. The task is to align those pieces with the generic model and use the aligned fiducial points (similar to the ones shown in Figure 3) to estimate the morphing transformation parameters that not only would align the fragments to the parent vase, but will also generate a full 3D model of the vase.

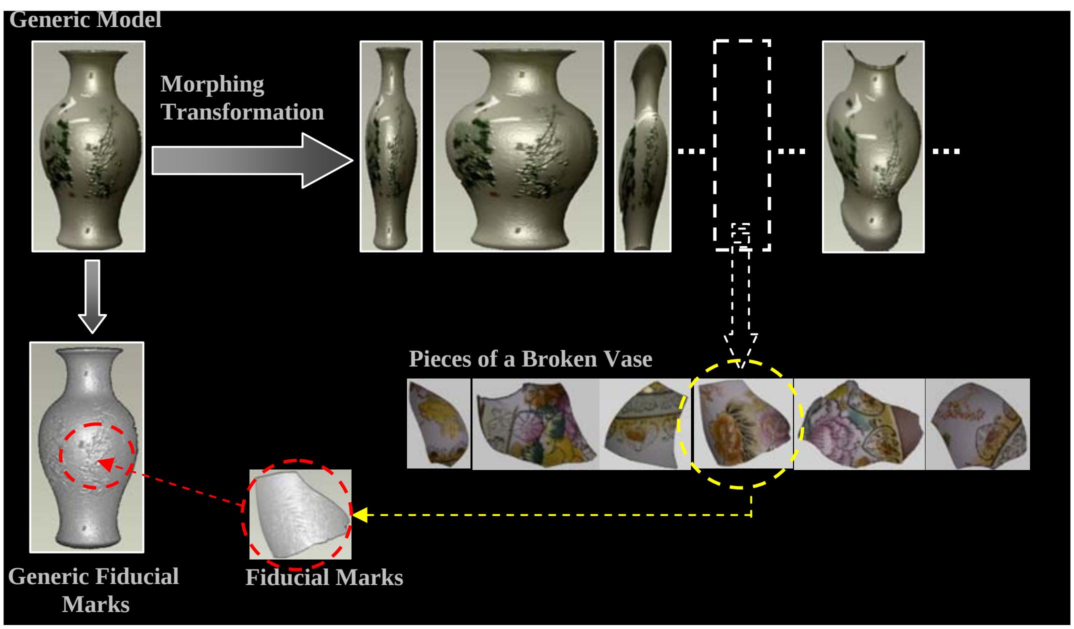

Figure 4: The key steps of virtual reconstruction of thin-shell artifacts using prior model and intrinsic fiducial points like the ones shown in Figure 3.

As the intrinsic points are based on the differential geometry of surface, they involve computing high order derivatives of the surface. To stabilize the computation of the fiducial vis-à-vis their sensitivity to noise, we propose to fit a B-Spline surface to the scattered data obtained from a range finder. An approximating B-spline smoothes out the surface prior to the computation of the fiducial points, and allows the data points residing on the surface to be obtained up to any degree of required resolution [4]. For example, to ensure continuity in torsion, tangents, and curvatures, on the B-Spline space curves including at the curves' boundaries, we require at least a fifth-order B-Spline to fit the space curves. We propose to use our method in [4] to fit an nth-order B-spline to scattered and unordered 3D data.

Intrinsic geometry has **NOT** been used extensively in 3D matching and when it was used it did not extend beyond rigid or similarity transformations. For example, in the work in [5], crest lines and crest points were used for 3D alignment under rigid transformations. By and large, most efforts in using intrinsic geometry were geared towards curves in 2D and relied on curvature information, which is a local geometric invariant under similarity transformation that does not carry beyond (i.e., does not carry over to affine or higher order transformations). Efforts by us as well as by others [6-10] on using curvature extremal points that are preserved under affine transformations were undertaken. The curvature extremal points include the high-curvature points or the corner points and zero-curvature point or inflection points. The high-curvature points are not affine invariant; yet they are robust to affine transformation and have been used extensively for shape matching. The zero-curvature points have been proved to be affine invariant [11] and were applied in numerous applications where shape matching was essential. The zero-curvature points have a major drawback in that they are sensitive to noise. To provide the similarity measures, the curvature extremal point usually must be combined with other geometric invariants such as the area bounded by three selective curvature extremal points [11, 12]. The area is a well-known relative affine invariant [11]. To obtain an absolute invariant, a ratio of two areas is computed and used as a good candidate for similarity measures. Other typical geometric features include line intersections [13, 14], centroids of closed-boundary region [15], knot points [16], etc.

In this proposal we will concentrate on nonlinear morphing transformations up to a 3^{rd} or 4^{th} order degree of nonlinearity that are well approximated by piecewise affine maps. We feel that we need not go beyond that degree of nonlinearity in lieu of the knowledge of the expert about the artifact, which makes the variations from the generic model easily captured by a 3^{rd} or 4^{th} order morphing transformation. This also makes the seeking of the fiducial points and the design of the invariants more of a tractable and manageable problem. We propose to derive and use fiducial points that are affine preserved locally under these nonlinear transformations. Examples of affine preserved fiducial points are shown in figure 2. With the fiducial points being local, they are well suited to deal with the partial fragment alignment problem. This is sharp contrast to other geometric invariant methods like moments [17] and Fourier descriptors [18] that are global in nature.

Reconstruction based on Local Geometry and Photometry

Once archaeological remains are excavated from a site, archaeologists are faced with the task of manually reconstructing each artifact from its fragments. This process consists of two major steps. The first is to identify candidate fragments that may be in close context within the same stratigraphic layer/level. This involves prior information about artifact provenience (which fragments are associated). The next step is to verify whether these candidates are indeed conjoining fragments by actually piecing them together. This task inevitably builds upon trial-and-error, iterating the two steps until the vessel is reconstructed. In order to integrate digital technologies to effectively assist archaeologists, a computational method that supports this task, if not fully automating it, becomes crucial. In contrast to the global model approach in the previous section, this necessitates a local approach in which only geometric and photometric information available in each fragment are utilized. Nevertheless, such a local approach goes hand in hand with the global approach to realize efficient and robust means that take full advantage of both human expert knowledge and computational power.

Geometric registration of 3D data has been studied in detail in the computer vision and graphics communities. The problem is motivated by the fact that, in order to reconstruct a complete 3D object, multiple partial views of the object must be acquired and fused together. The fundamental approach to this problem is to iterate between identifying corresponding points between two or more range images and estimating the transformation that puts them into alignment [22,37]. Various extensions to this basic approach [19,20,24,29,32,34,35,36], including Co-PI's contribution for realizing robust simultaneous registration [33], has been made in the past decade. Such 3D registration has also been one of the main research topics in a number of projects on digital archiving of cultural assets [21,28,31]. However, these approaches cannot be directly applied to the problem of reconstructing fractured thin-shell artifacts. Previous 3D registration algorithms essentially rely on the overlapping surface between the partial views of the original surface. For thin-shell structures, the fragments only share a thin strip at the boundary, which conveys very little information that cannot be reliably used. As a result, 3D registration of thin-shell fragments necessitates completely new machinery that exploits the commonality of geometric and photometric characteristics between non-overlapping surfaces. Note that this problem is considerably harder than traditional 3D registration including that of 3D solid objects where contacting surfaces can be used as overlapping geometric information [25,27]. At the same time, we aim to develop a computational method that works for general thin-shell objects unlike past work that assumes specific geometric properties such as axial symmetry [64].

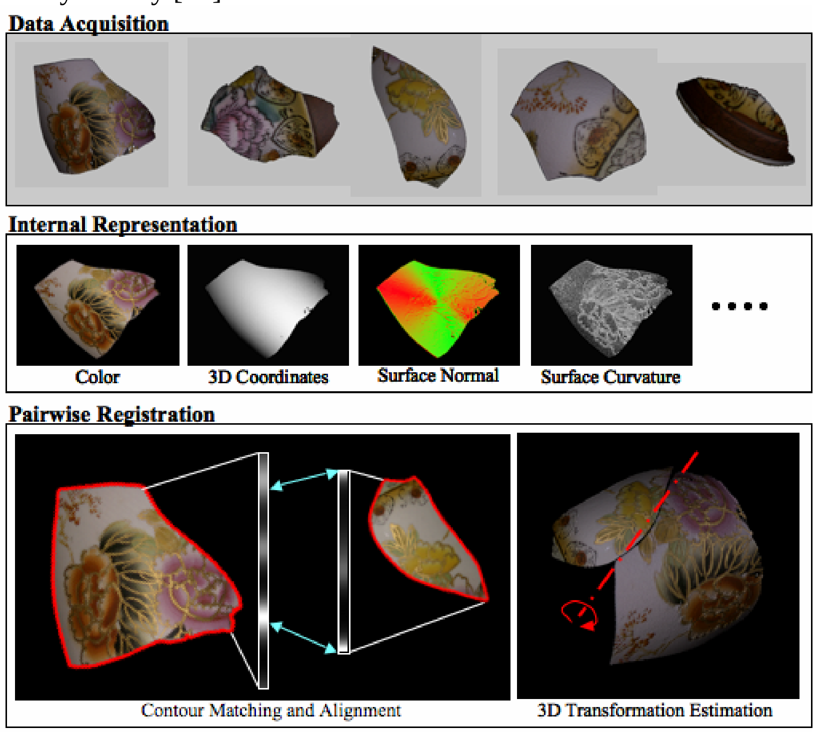

Figure 5: Key steps of virtual reconstruction of thin-shell artifacts using local geometry and photometry.

In this research program, we will develop a comprehensive framework for reconstructing a thin-shell artifact by registering its fragments based on their local surface properties. The method uses the continuity of the intrinsic surface properties across fragments and also the texture continuity often found on the surface as decoration. At the core of this research thrust is the theoretical investigation that leads to a novel error metric based on the geometric and photometric continuity and the derivation of a computational algorithm for formulating the registration as an optimization problem that minimizes this error metric. To the best of our knowledge, the proposed research is the first to investigate a comprehensive method for 3D registration of non-overlapping surfaces, which will also find applications beyond virtual archaeology including geometric reconstruction in medical imagery and in 3D sensing where surface overlap of partial views are often minimal and unreliable. Figure 5 depicts the key steps of the proposed framework.

At the core of the framework is a novel 3D pairwise registration method for non-overlapping surfaces, which determines candidate adjacent fragments by matching their contours and estimates the full 3D transformation to put them into alignment by evaluating the surface and color continuity. In the following, we layout our approach and discuss each key research issue.

Data Acquisition

The first step of our approach is to acquire geometric and photometric information of the archaeological remains. Towards that end we scan each fragment using a range sensor [30] and capture a high-resolution color image using a digital camera. We assume that the entire surface of the fragment can be viewed from a single viewpoint. This assumption holds true for artifacts that roughly have disc topology to begin with, including plates, bowls, and vases, which are the main excavated artifacts of interest here. This enables us to obtain geometric and photometric information of each fragment from a single view. In order to obtain 3D geometric information of each fragment along with its color information, we will use a pre-calibrated setup in which a digital camera is mounted on a laser scanner. Calibration is achieved by scanning and taking a photograph of a grid-textured box and providing corner correspondences between the range and color images. Since the camera is rigidly attached to the laser scanner, and once the calibration is done the entire setup can be moved freely, which is desirable for on-site in situ data acquisition. This setup, together with the fact that only a single view for each fragment is necessary, enables efficient data acquisition of the fragments, streamlining a process which can otherwise be extremely time consuming.

Internal Representation

Given the input range image of a fragment with a color image pre-aligned to it, we propose to investigate different representations of this data that are best suited for following our proposed approach. We mainly focus on using multi-dimensional 2D representations. Since, in general, the fragment can be assumed to have a disc topology, we may safely project both the 3D coordinates and color information associated to each 3D point onto a single plane. While the optimal plane and projection depends on the geometry of each fragment, to simplify the computation, we start by using the plane perpendicular to the average surface normal of the entire fragment and orthographically project all 3D points onto this global tangential plane. At each 2D point on this projection, 3D coordinates, surface normals, RGB color values, and their higher-order differential quantities will be stored. By interpolating these entities on the projection plane, we obtain a dense regular representation of the input data. This 2D representation of 3D and color information of each fragment provides a useful basis for further processing. Furthermore, the computation involved in transforming the input data to this internal representation and on this multi-dimensional 2D “image” has the potential of being accomplished in hardware, in particular, the Graphics Processing Unit (GPU), enabling efficient streamlined processing of the following algorithms.

Pairwise Registration

Once we have a set of fragments that potentially come from the same artifact represented as multi-dimensional 2D images, we may proceed to virtually reconstruct the artifact by locally piecing each fragment together. This task will be achieved by iterating pairwise registration of fragments in which two fragments are aligned to each other at a time. Analogous to what archaeological experts do, given a fragment, the first step of pairwise registration is to find a fragment from the remaining set that lies adjacent to the one at hand, and then estimate the full 3D transformation that puts the two fragments into alignment.

Contour Matching and Alignment: In order to determine the fragment that articulates with the fragment of interest from the pool of candidates, we will search for the specimen whose contour segment matches the fragment of interest the best. We detect the entire occluding contour of each fragment using the internal 2D representation. For instance, we may do this by fitting a parametric curve to the contour in the 2D projection using active contours [23,26]. Once we extract the closed contour curve, we may represent it as a one-dimensional line with differential geometric characteristics of the curve associated to it. For instance, we may encode 3D curvature characteristics of the curve including the torsion along these lines. Then, matching can be accomplished by estimating the best matched segments between any two contour lines using algorithms such as dynamic programming matching. Note that such string matching algorithms will enable matching of contour segments which are partially stretched or squashed, providing robustness against the difference of projection directions in the 2D internal representation.

In order to robustly estimate the matching contours, especially against noise and gaps due to natural decay of fragment contours, we will formulate this as a hierarchical coarse-to-fine optimization problem by sub-sampling points along the contour curves. Furthermore, we propose to encode geometric characteristics of the ceramic surface in addition to those of the curve to enrich the contour representation. For instance, at each point on the contour curve, we can compute and assign the curvature of the tangential surface in the normal direction to the curve. By reducing fragment contour matching and alignment to a 1D string matching problem, we are able to efficiently match and align potentially adjacent fragments. Note that, while determining the best matching fragment is accomplished by an exhaustive search through the fragment set, this reduction in dimensionality significantly reduces the computational cost for evaluating each candidate fragment. Furthermore, this search can be sped up by narrowing down the search space (the set of potential candidates) by utilizing the results of the aforementioned global model-based method.

3D Transformation Estimation: Given two fragments whose contour segments match, we will estimate the 3D transformation that aligns one fragment to the other. The result of fragment contour matching directly tells us the 3D transformation that aligns the contour segments. This transformation essentially describes the in-plane rotation of the 2D internal representation and a 3D translation between the two projection planes. Thus, what is left to be estimated is the global rotation in 3D space. However, since we already know that the given contour segments should align, the problem reduces to estimating a one-dimensional rotation about the contour segment. One may imagine a hinge as an analogy. We have placed the two sides of a hinge next to each other by aligning the contours, and we now seek to estimate the optimal rotation that puts one side in alignment to the other.

We estimate the remaining 1D rotation by formulating the problem as an iterative optimization problem in which the error is evaluated in terms of geometrical and photometrical surface continuity. First, we compute the 3D medial axis of the matched contour segments. Then, we recompute the 2D projections such that each of its projection planes is a plane passing through the common 3D contour axis and its normal is the fragment's global surface normal. At each step of the iteration, we project one segment's 2D representation to the other's given the current estimate of rotation and evaluate the surface continuity error. The surface continuity error can be defined in many different ways. One may define geometric continuity as the smoothness of principal curvatures, Gaussian curvatures, or mean curvatures in a strip about the matched contour segments. Note that, if we use Gaussian curvatures, we may avoid recomputation of the 2D representations at each step resulting in significantly reduced computation with the price of potential ambiguity due to less discriminative power of a scalar differential quantity. As for the photometric continuity error, we may use color and its differential quantities including edges in a thin strip around the matching contour, again evaluated perpendicular to the contour segment axis. The error function will be a linear combination of the geometrical and photometrical continuity errors.

We will thoroughly investigate the mathematical foundation of this iterative pairwise registration method in order to realize robust registration of fragments. As we have demonstrated in previous work [33], we will incorporate robust statistics to handle potentially noisy estimates of geometric and photometric differential quantities used in the error metric. Furthermore, we will explore the use of multi-scale representations, in terms of the support region for computing the error metric, including the width of the strip to be used and also the sub-sampling of the surface points along the matching contour segment combined with canonical smoothing as in traditional scale-space theory. Such multi-scale optimization will result in increased efficiency and robustness.

Global Framework

Using the novel pairwise registration method as the core engine, we will develop computational methods that virtually reconstruct the original shape of the archaeological artifact by iterating local reconstruction. The main approach we take will be to literally build up the artifact by putting the fragments together one by one. We start with a single fragment and rank the final error for all remaining fragments after estimating the potential matching contour segment and computing the minimized surface continuity error. Then, we attach the fragment with the lowest error to the fragment. This is iterated until there is no fragment left. The continuity error may also be weighted by the length of the matched contour segments to encourage alignment of fragments with longer matching contour curves. This is generally true as more fragments are aligned together. Note that this process can start with multiple fragments and run in parallel. In order to be conservative, one may threshold the smallest error and chooses not to align any segment to the fragment at hand. The main focus of our research will be to theoretically investigate how to avoid growing an erroneous shape by registering sub-optimal fragments together and to derive efficient computational methods to backtrack in such cases. We will also investigate data structures and algorithms to realize this virtual reconstruction as an interactive system. We believe that this goal can be achieved by pre-computing contour matching and registration errors for all pairs of fragments and effectively visualizing suggestions as the reconstruction progresses, seamlessly integrating an expert in the loop.

Vision-based Recognition using Decorative Information--Helping with the Selection of Priors and the Stitching of the Fragments

The combination of complex and low quality painted and printed surface designs on British Export Ceramics makes BEC a uniquely viable and valuable data set for research and development of a robust visual recognition system (one that will also have applications far beyond archaeology). Historical Archaeology ceramic analysis involves the identification of ceramic decorative style from a range of possibilities. Moreover, vessel surfaces can be evaluated for ‘use wear’ patterns (scratches left from repeated impacts by a knife or spoon) and depositional deformations (impacts to the ceramic fabric as a result of pre- and post-disposal context such as spalling of glaze after exposure to fire and mineral staining from a soil matrix). Furthermore, BEC come with a rich record of information important for a 3D prior model and for photometric, texture, geometric, catalog, and categorical parameters. Such complex conditions motivate the need for multi-scale representations based on qualitatively defined, robust image features. In one scenario, vision-based recognition will allow individual small fragments to be assigned to a query artifact and conversely, will permit efficient fragment relocated for retrieval from within a large collection. In another typical scenario, vision-based recognition will allow for broad comparison and measures of surface patterns within large ceramic assemblages comprised of multiple vessels of multiple types bearing an equally large range of decoration. It should be noted that target artifacts can be structured multi-part assemblies or, in some cases, a configuration of subordinate sub-parts (meaning missing fragments can be mediated). This ceramic recognition involves three important steps: 1) extracting appropriate image appearance features and capturing the decorative surface patterns; 2) selecting (indexing) candidate structures from a large database of structured models with similar decorative information; and finally, 3) verifying the candidates in order to select the most likely interpretation.

Our approach for representation and recognition of objects from their decorative information includes the enhancement of underlying scale-space representations in order to improve the visioning method robustness to degradation ratio, as well as the incorporation of domain-dependent appearance information into the structural index in order to reduce indexing ambiguities. To tackle the indexing and matching problems, we will investigate mechanisms for structural representation that will allow us to perform robust matching of scale-space features associated with surface patterns.

Deep-structure Features and Scale-Space Representation

The visual processing of images will be comprised of a two-step procedure performed by low-level feature detection methods followed by higher-level, task dependent, processing. In this case, any two images exhibiting identical visual patterns will yield the same visual processing result. In our research, in order to capture the decorative information associated with surface fragments, we will investigate a small subset of all possible operationally defined features, namely those that can be expressed solely in terms of local structure of scale-space derivatives. We use the approach of Gaussian scale-space so that multi-scale local features may be expressed as features at a finite scale. We will refer to these features as deep-structure appearance features.

Several researchers have developed feature detectors and representation models for capturing deep-structure features. For example, it has been proven that by using deep-structure features one may reconstruct the image from the multi-scale zero-crossings of the Laplacian [48, 49]. The differential attributes of scale-space features are known to be invariant to rigid transformations [45] and make them ideal for characterization of surface makings. To characterize the information associated with decorative patterns on sherds, we will use feature detectors to select a number of points of interest or attention in the image. In principle, we will use scale-space blob-, ridge-, corner-, edge-, and critical/top-points to capture the shape of a decorative pattern. By suitable scaling and normalization we obtain invariance to spatial zooming and intensity scaling as well, but the resulting system has the property that most low-order invariants vanish identically at the extrema of critical points of the original (zeroth order) image, and thus do not qualify as distinctive features. Thus, when considering feature points, other distinctive features will have to be used to guarantee proper characterization of the shape parameters (e.g., interest point plus differential feature vector). Figure 6 presents an overview for constructing the deep-structure representation from a set of differential features for surface markings.

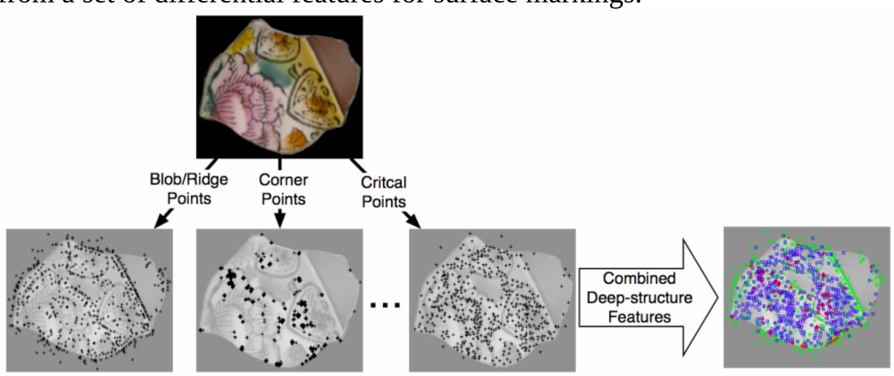

Figure 6: Extracting the scale-space interest points and construction of deep-structure representation.

Hierarchical Representation of Decorative Information

In capturing the details of decorative information represented as scale-space features using a hierarchical representation, we want to encode the neighborhood structure of a set of interest points, explicitly relating nearby points to each other in a way that is invariant to minor perturbations in feature location. Moreover, when local neighborhood structure does indeed change, it is essential that such changes will not affect the encoded structure of decorative patterns (image) elsewhere. The Delaunay triangulation imposes a position-based neighborhood structure with exactly these properties [53]. It represents a triangulation of the points that is equivalent to the nerve of the cells in a Voronoi tessellation [54, 59]. The edge set of our resulting graph will be based on the edges of the triangulation. Our second goal is to capture the scale-space ordering of the interest points to yield a directed, acyclic attributed graph, with coarser scale points directed to nearby finer scale points. Figure 7 represents the local structure of the hierarchical graph associated with a small subset of scale space features. Our proposed attributed graph-based representation of interest points associated with decorative patterns promotes a convergence of graph algorithms and computer vision. Since degradation and/or missing portions of decorative patterns may perturb the image and its associated graph structure, we also need to ensure that our similarity measure is insensitive to minor structural perturbations. To address these needs, we have investigated a structural representation based on spectral graph theory [57,60]. Specifically, we will derive algorithms for our hierarchical representation of deep structures associated with surface markings and trademarks.

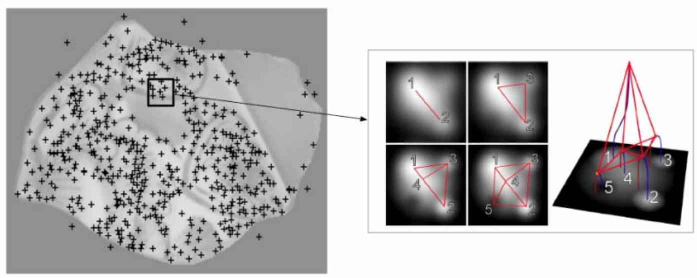

Figure 7: Construction of hierarchical representation of deep-structure via tessellation of scale-space features.

Structural Indexing

For large image databases, using exhaustive search to find the best match to a query is infeasible. Indexing mechanisms are essential for fast retrieval of a small set of candidates to which a more precise matching procedure should be applied. If database images and the query image are represented as attributed hierarchical graphs, candidate graphs will share a large subgraph with the query graph. Thus, the problem appears to be that of quickly selecting from a large database of attributed graphs those graphs that share a large subgraph with the query graph. To summarize our intended approach, we propose to develop a novel encoding of the topology of an attributed graph that is invariant to minor perturbations in the size of the graph. These encodings, or topological signatures, will be derived from topological decompositions associated with a graph. Our previous work on spectral analysis of a graph's adjacency matrix reflects only the graph's structure and not the information encoded in a node or edge. Our preliminary investigation [61, 62] confirms that the stability analysis of spectral signatures also holds for non-binary matrices. We would like to explore the properties of eigenvalues computed on matrices that encode not only structure but also attributed node and edge properties as values at diagonal and off-diagonal entries of matrix representations associated with a hierarchical structure. Assuming the existence of a small number of subgraphs (vocabulary of parts) shared among many models, a number of researchers [42, 43, 63, 56] used a two-stage indexing process in which image structures were matched to the part vocabulary, with parts "voting" for candidate models. Sengupta and Boyer [57] used a spectral graph decomposition technique for the partitioning of a database of 3-D model graphs, whose nodes represented 3-D surface patches. Several alternatives for indexing shape features have been proposed. The most popular ones are based on decision trees [58], interpretation tables [46], hashing [51], and nearest neighbor searching. In recent years, nearest-neighbor (NN) techniques have become very popular for feature-based retrieval applications [39].

Matching of Surface Markings and Trademarks

The matching algorithms of hierarchical representations of pattern associated with ceramic decorative information are a major component in recognition and identification of artifacts. Previous work on matching has typically focused on the problem of finding a one-to-one correspondence between features captured in two graph-based representations. In general, it is quite common that, due to degradation of designs or segmentation errors, a single feature (node) in one fragment (graph) can correspond to a collection of broken features (nodes) in another fragment (graph). Hence, we seek a many-to-many correspondence between image features. In recent work [42], we presented a preliminary framework for many-to-many matching of attributed undirected and directed graphs. To summarize our approach, in order to match two attributed graphs, we first embed them into a single Euclidean space using a lowdistortion graph embedding technique of [38, 52], and then match them as weighted point sets in the Euclidean space [41]. We propose to develop many-to-many matching procedures for partial matching of edge-weighted attributed graphs. Since our attributed graphs come from visual data associated with decorative information, which is susceptible to noise and degradation, the matching framework must be able to cope with local perturbations of graphs.

Several researchers have developed algorithms that find one-to-one correspondences between graph nodes. Shapiro and Haralick [58] proposed a matching algorithm based on comparing weighted primitives using a normalized distance for each primitive property. Kim and Kak [50] used a combination of discrete relaxation and bipartite matching. Pellilo et al. [55] devised a quadratic programming framework for matching association graphs, while Gold and Rangarajan [47] used graduated assignment for matching graphs. The problem of many-to-many graph matching has also been studied, most often in the context of edit-distance (see, e.g., [44, 65]). In the context of line and segment matching, Beveridge and Riseman [40] addressed this problem via exhaustive local search.

Work Plan and Milestones

The proposal is a joint effort of five PIs, and three PhD students. Throughout the project we shall maintain a quarterly contact and ongoing discussions with our collaborators at the Living History Center at the Independence National Historic Park, including NPS Archeologist Jed Levin, who will facilitate our access to the archaeological database. Dr. Jeppson (Co-PI3) will provide the prior models and the historical findings surrounding the excavations that could be translated into generic models. Dr. Jeppson along with Dr. Muschio (Co-PI4) will also be taking the leading role in the dissemination part in our project, in particular as it relates to the use of virtual reality and augmented reality technology to develop strategies for making new media resources available for education, tourism, and commerce. Starting the second year, the PIs will develop a multidisciplinary course in Computation Methods in Digital Archaeology. The supported PhD students (denoted by PhD1, PhD2, and PhD3) are to conduct both research and implementation.

YEAR 1:

• **Reconstruction based on Global Geometry:** Develop the generic model (or family of models) and access the class of morphing functions that will be covering a wide class of artifacts (PI and PhD1). This will involve collaborative selection of BEC type specimen for scanning (whole and in part) for a prototype study of cognitive, prior typologies; ethnoarchaeological participant observation study of the specimen's assembly by a ceramic specialist to elicit cognitive typologies applied in the mending process (both tacit, experience-based, knowledge and formally acquired knowledge); and observation study of the specimen's assembly by a non-expert volunteer.(Co-PI4)

• **Reconstruction based on Local Geometry and Photometry:** Develop the data acquisition setup including its calibration method and collect data with ground truth by artificially producing fractured thin-shell objects and also collect data of excavated artifact fragments at the Living History Center. At the same time, start collecting contextual information from the excavated site data. Investigate different alternatives for internal data representation and derive and implement fragment contour matching and alignment. Thoroughly evaluate contour matching by applying it to fractured flat 2D surfaces (jigsaw puzzles) and the aforementioned artificial data (Co-PI1 and PhD2).

• **Recognition based on Decorations:** Develop a composable extension of deep structure features to support scale-space representation of surface markings, heterogeneous feature types, and multiple differential invariance; development of algorithms for construction of graph-based representation for deep structure features; implement a prototype system for these components (Co-PI2 and PhD3).

• **Expert contribution:** Index and developing the anthropological prior findings in the form of possible generic objects for the fragments database that would be used across this project. (Co-PI3, Co-PI4 Archaeologist Jed Levin, PI, and PhD1).

YEAR 2:

• **Reconstruction Based on Global Geometry:** Develop the class of intrinsic fiducial points that are preserved under the morphing transformations, and assess the degree of their robustness under deviation from these assumptions. Develop the absolute invariants constructed based on these intrinsic fiducial points (PI and PhD1).

• **Reconstruction based on Local Geometry and Photometry:** Derive the mathematical foundation of defining the geometric and photometric surface continuity metric and the algorithm of minimizing it. Implement the results as a prototype system for matching and aligning fragment pairs and thoroughly evaluate its effectiveness on simulated data (Co-PI1 and PhD2).

• **Recognition based on Decorations:** Develop a mechanism for spectral encoding of hierarchical structure; develop evaluation mechanisms for different feature types; implement the indexing mechanism and extension to incorporate surface marking information; integration to prototype system and testing the indexing performance on a surface marking database (Co-PI2 and PhD3).

• **Expert Contribution:** Index and supply the anthropological prior findings in the form of generic objects based on the surface marking data extracted using part 3 of our proposed research for the fragments database that would be used across this project. Import the developed software components to Public Archaeology web-site (Co-PI4, Co-PI3, Co-PI2, and PhD3).

YEAR 3:

• **Reconstruction based on Global Geometry:** Develop and test the matching global algorithm on fragments data supplied by the NPS Independence Living History Center Archeology Lab (PI and PhD1).

• **Reconstruction based on Local Geometry and Photometry:** Investigate the theory and algorithm for global registration based on precomputed pairwise registration of all fragments. Integrate the method into the aforementioned system and thoroughly evaluate its accuracy and effectiveness using both artificial and real archaeological data (Co-PI1 and PhD2).

• **Recognition based on Decorations:** Develop a many-to-many matching algorithm able to deal with partial matching; implementation of partial many-to-many matching; test and integration to prototype system; evaluation of a surface marking database (Co-PI 2 and PhD3).

• **Expert Contribution:** Disseminate our findings on the Public Archaeology web-site. These packages will be supplied to and evaluated at these selected places for digital media manipulation, data exchange and archiving. Finally the reconstruction codes will be released via project web-site for use by Archaeology, digital-media, vision, and graphics communities (Co-PI3, Co-PI4~~,~~ Co-PI1, and PhD2).

Results from Prior NSF Funding (last 5 years)

Fernand Cohen's prior NSF support in the last 5 years is Integrating Sensor Networks in Undergraduate Curriculum: A Marriage of Theory and Practice (PI: J. de Oliveira and F. Cohen) (2007-2009). The primary arching goal of this proposal is the integration of a practical approach to complement the learning and understanding of wireless sensor networking concepts and embedded programming methodologies into the undergraduate curriculum and learning process across other Science, Technology, Engineering and Mathematics (STEM) disciplines.

Ko Nishino is a new investigator and has not received any funding from NSF in the past.

Ali Shokoufandeh's prior NSF support includes: 1) SGER: Algorithmic Infrastructures for Knowledge Management (2001-2004), where we designed abstract data structures and algorithms have been developed to manage knowledge networks with application to computer vision and pattern recognition; 2) ITR: Representation and Design of Heterogeneous Structures (2002-2005): the project studies the development of discrete modeling structures for representation and design of three-dimensional heterogeneous objects; and 3) ITR/IM Novel Indexing and Retrieval of Dynamic Brain Images (09/01/02-09/01/05): the project supports development of retrieval models for 3D fMRI brain images using cosine metric, canonical set, development of visualization and comparison toll for fMRI images, and tools for maintaining large collections of fMRI datasets.

Patti Jeppeson has no NSF funding in the last 5 years.

Glen Muschio has no NSF funding in the last 5 years.