208939

SHORT TITLE:
Computer-Assisted System for the Reconstruction of Shattered Objects

NIJ Grant: 2000-RB-CX-001.   Final Report

FULL TITLE:
Development of a Computer-Assisted System for the Reassembly of Fragmented Plate
Glass and Other Surfaces Splintered by Violent Acts

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I. 1. Abstract

Reconstruction for forensic purposes of shattered or otherwise damaged objects has been a
painstaking, if not impossible, undertaking. The forensic crime scientist and the
archaeologist share this challenge. A pilot project, funded by the National Institute of
Justice (grant 2000-RB-CX-001) experimented with several avenues of approach to this
problem of reassembly by using the 627 fragmented pieces of a pane of glass from a crime
scene. I was approached by staff members of the Minnesota Bureau of Criminal
Apprehension (BCA) Forensic Science Laboratory because I was developing a means to
restore a Greek Bronze Age wall painting from Pylos (ca. 1350 B.C.E.) fragmented into
4750 pieces (Appendix A) and a Greek temple (ca. 150B.C.E.) demolished by vandals about
1500 years ago (Appendix B).

From the beginning the outlook was to reach beyond a one-time reassembly or even the
narrow purpose of reassembling shattered glass. Rather, we sought to develop a
computer-assisted system which would be broadly applicable to a variety of reconstruction
tasks. For this reason we paired the pane of glass with the Pylos fresco fragments as
representing two of many possible polarities (Appendix A). If the solution worked for
both, then the potential for general application was broadened.

This first venture with the glass pane proved to be successful. The project developed
a matrix of programs which offer the ability to graphically manipulate geometrical
shapes that are attached to an interactive database. Joins of pieces discovered in the
computer graphics routine were tested by ground-truth with positive results.
This achievement invites the obvious next step: the development of the application
to increase the speed and efficiency of the computer matching of joins as well
as to broaden the kinds and shapes of material objects that our application will accept.
Another goal is to adapt the commercial, proprietary software of our matrix to a
user-friendly, stand-alone PC program easily distributed to forensic crime laboratories
and archaeological and architectural reconstruction projects.

II. FORWARD

II. 1. Background

Physical objects shattered and then scattered by human agency have been difficult, if not impossible, to reconstruct into their original whole. The forensic scientist and the archaeologist both have this problem. This project came about because the forensic staff at the Minnesota Bureau of Criminal Apprehension (BCA) was unable to reconstruct, beyond a few portions around the outer edges, a 4-by-8 foot glass pane, a crucial piece of evidence in the investigation of a possible homicide in Minneapolis. After months of jigsaw puzzle-fitting, the outer perimeter was assembled, using the feature of finished, straight edges, paint and sealant at margins (Figs. 1 and 2). At that time, Laura Nelson, a forensic specialist at the BCA learned of my fresco research in Greece and asked if I could assist with the reassembly of the modern pane of glass. Prior to our being brought into this project, Laura Nelson and her staff conducted an exhaustive survey of forensic laboratories in a quest for guidelines as to how to proceed. She learned that there had been no successful reconstructions of record, including the protracted attempt with the windows of the ill-fated TWA 880.

1. B.C.A. Pane of glass

As in previous similar undertakings, the reassembly ground to a halt. Just too many permutations. Taking account of the eventual digitized pieces of glass, the number of sides range from 3 to 8, with 4 sides per fragment the average. This brings the number of possible permutations for the matching of sides to around 76 billion. This quantity was reduced to a manageable level by the adoption of several geometrical premises and filters of surface and edge conditions.

II. 2. Organization

The organization team consisted of the PIs Laura Nelson and Frederick Cooper; Anne Hollister, a graduate student in Classics at the University of Minnesota, responsible for the publication of the Bronze Age frescos; Todd Brenningmeyer, a graduate student in Art History at the University of Minnesota and a specialist in GIS and an honors student. Charles Griebel, a graduate student in Greek archaeology who is now an Information Technology Systems Manager, who served as a technical advisor.

2. B.C.A. Pane of glass, detail of paint

At the outset, we did not have yet the experience to ascertain what are the diagnostic characteristics of a fractured and shattered pane of glass to allow a reconstruction of the splintered pieces of glass (shards). We established the following protocol in order to develop a cataloguing system:
    1) minimal handling of the shards
    2) a comprehensive accounting of all available and detectable features in order to avoid subsequent rehandling of the shards
    3) simple recording procedures enabling the nominal training of volunteer student help.
    4) It was imperative to formulate a set of features held by the glass shards which would serve as a contributing factor in making joins. Careful measurements with a micrometer revealed that the pane, which had been set in an old building, had a variable thickness from thinnest at top to thickest at the bottom (.240 to .247 inches, but converted into metric).

The pieces of glass were gathered carefully at the crime scene but, unfortunately, they were not mapped prior to lifting. The inside or outside faces of the pane can be distinguished only by secondary evidence: streaks or speckles left from a careless face extant washing, a painted sign, traces of blood and footprints.

III. THE NIJ PROJECT

III. 1. Staff

1) Frederick Cooper, the Project Director, coordinated the activities, maintained oversight of progress in the three other components, suggested and encouraged improvements or alternatives in methodology as the project evolved.

2) Charles Griebel focused on the development and implementation of an SQL database to store and access elements of each shard (catalogued during the initial pre-grant project). This analysis also involved filtering the database into most likely joins using a series of SQL statements automated through perl scripts. The output from this analysis provided the basis for the project's second phase.

3) Todd Brenningmeyer focused on integrating the database and the output of the filtering operations into an application built around Geographic Information Systems (GIS) technology. This system examines both the attributes gathered during initial laboratory work and the geometric properties of each digitized shard to identify most likely matches from the thousands of potential joins catalogued during the original phase of this project.

4) Research assistants performed the laboratory ground-truthing. The shards identified as potential joins were identified and tested at the University of Minnesota. Two University of Minnesota research assistants were responsible for examining the fragments identified through the GIS and database queries to determine whether the application was in fact identifying true matches. The results were then relayed to Charles Griebel and Todd Brenningmeyer who implemented any necessary changes to applications or methodologies. The research assistants were responsible for improving the record sheets and for entering additional data into the database.

III. 2. Technology commentary

As already emphasized in the accompanying text, the development component of this project extends the rapid and current computer technologies to new forensic applications. At the heart is the deployment of the constant advances in the science of Geographic Information Systems (GIS). After several trials with a variety of CAD (AutoCAD) and database (MySQL) programs, we have provisionally settled on ArcInfo, a GIS product of ESRI, Redlands, California. Yet, there are restraints. The database attribute of ArcInfo does not have a sufficient robust search engine to efficiently accomplish this application. Nor does the graphics component have the flexibility of AutoCAD. These restrictions can be overcome by scripting a separated application using ESRI's program MapObjects.

III. 3. Evidence Preparation

Each shard was assigned a barcode and photocopied on individual, preprinted sheets (Fig. 3). Crucial to development of a graphics-cum-database retrieval system of shattered pieces is to assign a unique value for each piece and to place the drawing of each in a unique position within a vectorized, that is to say, within a coordinate grid in the CAD program. The purpose is to avoid confusion caused by overlapping images on the one hand and by duplication of inventory numbers on the other. We devised a barcode with a set of 4 labels for each unique number: one for each shard, one for the inventory sheet, one as a storage locator, and one in reserve.
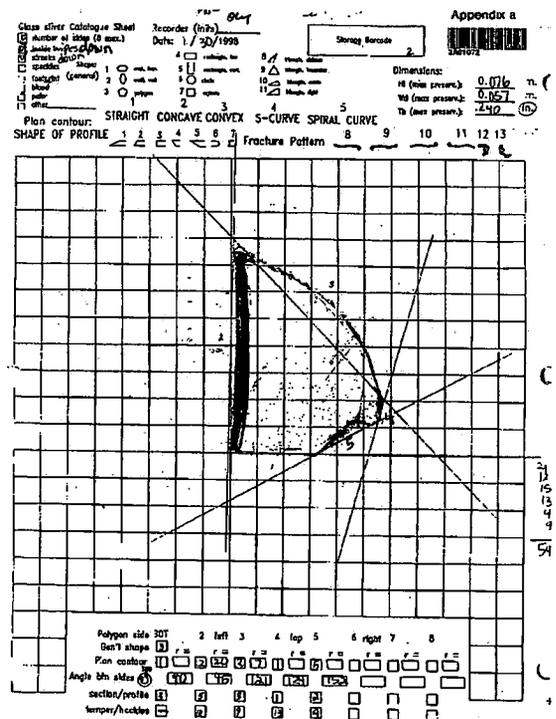
3. Pane of Glass. Typical inventory sheet

An inventory numbering system doubled as the coordinate system. None of the unassigned glass fragments were larger than 20 cm. x 20 cm., which became the cell size of a coordinate table with the position designator at the lower left corner. In the numbering system, a prefix of "2A0" represented an arbitrary constant, assigned to allow for expansion of the serial sequence. The last four values begin with an initial 1000 (i.e., 2A01000). The sequence increments by 2,

each interval representing 2[0] centimeters in
the lower left position of the y-axis of the grid
system and the second position of the 1000,
increments for 20 cm. for the value of the x
axis. The result is an incrementation where the
second and forth values increase at even numbers.
For example, the barcode inventory number of the
sheet in Figure 3, 2A01072, places the lower left
corner of the cell containing the image of the
shard at x = 100 and the y = 720; that is, 0.100,
0.720 within the AutoCAD or Arc/Info drawing
space. A shard with 2A02848 falls at x= 280 cm.,
y= 480 cm. The cell comes immediately above
2A02846 and adjacent and to the right of 2A02648.
In AutoCAD these values are the equivalent of
drawing units and are scaled accordingly. The
columns and rows of digitized glass fragments in
Figure 4 illustrate this kind of positioning.
The interrelationship between unique-key
inventory number and unique-grid position in the
graphics table simplifies the GIS operation of
the project.
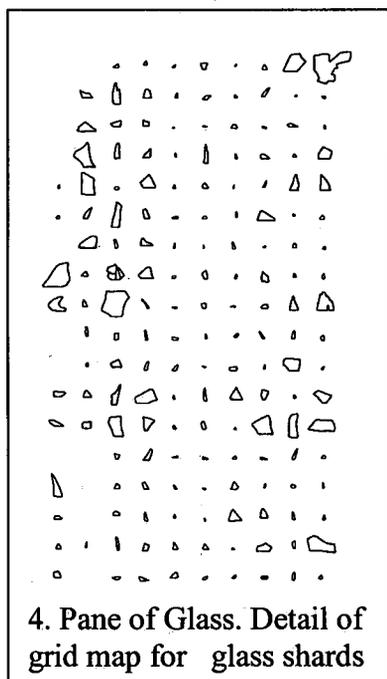
4. Pane of Glass. Detail of
grid map for glass shards

Two AutoCAD functions, "move" and "rotate", are
particularly useful for the assessment of
potential joins identified by the SQL filtered
queries discussed above. In AutoCAD, the
digitized images of a source and a target piece
are located by inventory/coordinate number using
the current cursor coordinate status display on
the screen. The images are copied to a
workspace; a preliminary sorting eliminates
unlikely joins. Alternating between "move" and
"rotate" AutoCAD functions, a trial fitting of
the pieces yields potential joins as in Figure 5.
Successful fits here are then "ground-truthed" by

actual pieces in the lab.
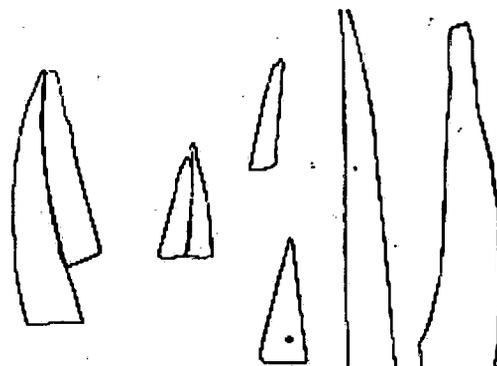
5. Pane of Glass. AutoCAD matching of SQL filtered
results

At this stage, cross-section characteristics
were recorded: thickness, the vertical profile
(Figs. 6 and 10) and type of hackle and
feathering (Figs. 7 and 9) for all sides around
the perimeter. Additional attributes compiled at
this time include the number of sides, the
maximum thickness of the piece, and various
surface inclusions that were evident: paint,
streaks from recent cleaning, blood, footprints,
speckles and other miscellaneous elements (Figs.
8 - 10). The 526 bar-coded pieces were arranged
in storage boxes out of the necessity to free up
laboratory space during development of the
program and processing of the data.
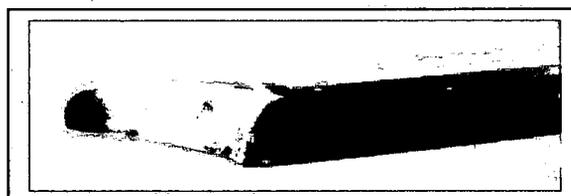
6. Pane of Glass. Fracture edge showing cross-
section, feathering and
hackles
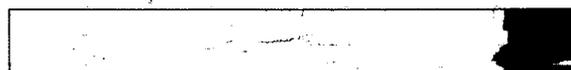
7. Pane of Glass. Fracture edge showing feathering
and hackles

Further analysis depended only on the inventory
sheets. Inscribed polygons were drawn within the
photocopied image of each shard using cords
across curving contours. The types of arcs and

Glass sliver Catalogue Sheet
- ☑ Number of sides (8 max.)
- ☑ inside wipes down
- ☑ streaks down
- ☐ speckles   Shape: 1 ⬭ ₀
- ☐ footprint (general) 2 ◯ ₀
- ☐ blood   3 ⬠ ₚ
- ☐ paint   1
- ☐ other____

8. Pane of Glass. Detail of inventory sheet, list of surface attributes
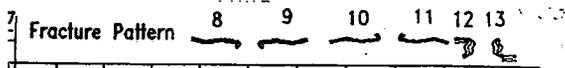
9. Pane of Glass. Detail of inventory sheet, encoded feathering patterns
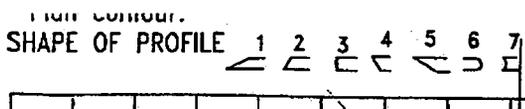
10. Pane of Glass. Detail of inventory sheet, shape of profile

their radii were noted and measured by placing shards on a concentric template (Fig. 11). An overall shape and size were noted and measurements taken along the sides (Fig. 12).
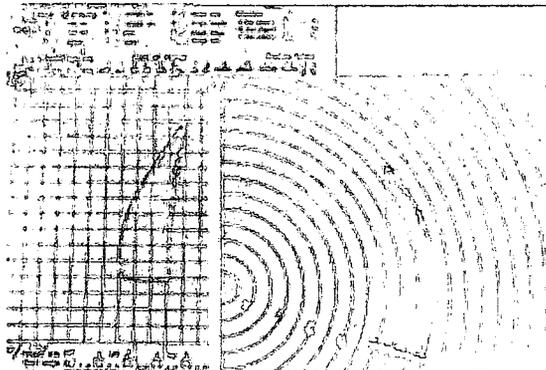
11. Pane of Glass. Template for sizing and radius measurements

12. Pane of Glass. Entry boxes for measurements around perimeter

Angles around the polygons were scaled by protractor and, once entered into the database, the sums were checked for accuracy. At the offset, the option of simply scanning into image files the individual fragments was rejected in

favor of digitizing each piece using a digitizing tablet operating under AutoCAD Map 2000 from AutoDesk in order to create a vector-based geometry (a topology) for graphic as well as mathematical manipulation in a computer search for potential matching pieces (Fig. 13). As remarked above, there was no attempt to formulate polylines made up of Euclidean arc segments and straight lines. Nonetheless, the polylines were closed to make true polygons which, among other advantages, allows for areas of each shard to be calculated. The total time devoted to these preparations amounted to less than 125 hours, a remarkably short period.
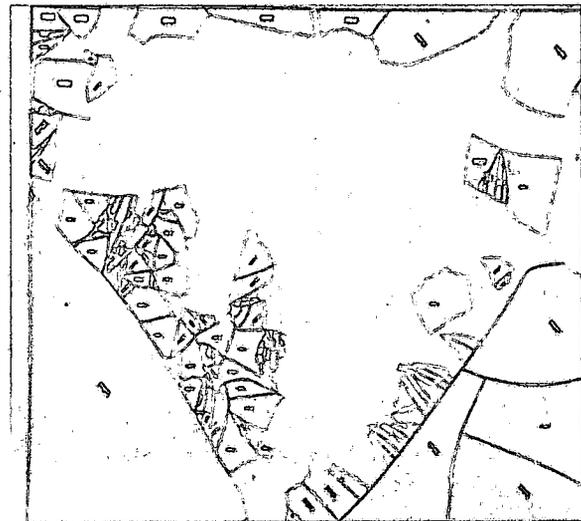

13. Pane of Glass. Digitized plan of B.C.A. restoration

In preparation for the next, or trial-and-error, stage, we formulated the following principles:

    1) Concave curves match convex breaks when the radii are equal ;

    2) Straight breaks abut their counterparts;

    3) Angles between adjacent sides of a given shard fit either into the supplementary angle on the perimeter of a potential join, or into the supplementary angle formed by an intersection of two or more fragments (Fig. 5, left);

    4) Fracture patterns and hackles on one edge had to conform with the joining fragment (Fig. 6 and 7).

From the offset we realized that precise and time-consuming measurements of the sides would yield false values. That is to say, we discovered that plate glass does not fracture into primary geometrical lines and shapes: arcs are not those of a circle; instead, any given curve has variation in lengths of radii and in location of center points. Thus, values of a relatively high order of accuracy were obtained from scaled measurements using template overlays

of concentric curves.

In the following account, all these features are called attributes. All elements were entered onto a database and, when appropriate, the attributes were reduced to Boolean expressions for queries using operators in database, GIS, and CAD statements.

DBase III was adopted for the primary database. A convenient version runs on the HP 48 series of handheld computers, ideal for on-the-move entry in the field and an inexpensive alternative to multiple portable PC stations. DBase III exports to all Windows-based databases and GIS programs, including ESRI and AutoCAD.

III. 4. Project Phase I.

The development phase of the project focused on incorporating the catalogued attributes of each fragment into a system that could identify the most likely joins using database (primarily SQL) queries and the geometric properties of the shards. Two separate GIS packages were employed for the initial development and testing of the application: ArcInfo 8.xx and ArcView 3.xx. These packages are standards in the GIS industry. A third application, AutoCAD Map 2000 from AutoDesk San Rafael CA., was used in the original digitizing of the collected fragments. The current application was developed using Avenue (a proprietary scripting language of ESRI's ArcView application). This development environment provided access to the robust GIS tools that are embedded within ArcView, allowing not only queries of the embedded SQL database but also the rapid retrieval and display of digitized fragments and scanned versions of the original laboratory reports. These reports were scanned into .tif format and each scan was tied to its corresponding entry within the database tables.

Two additional applications (ESRI's MapObjects and IMS platforms) were examined for possible use in future versions of the applications. MapObjects 3.1 from ESRI, was identified as the best package for final application development. MapObjects is a collection of Active X components that provides the functionality of ArcView and much of ArcInfo within Microsoft's Visual Basic development environment. This package would enable the final application to be ported to any windows based PC. ArcIMS is an internet enabled GIS platform that provides many of the functions of ArcView but delivers this functionality through internet or intranet browsers. The application would be maintained within a

centralized server and delivered as needed to assistants in the research laboratory or elsewhere. The advantages of this application relate to the centralized storage of the database that can be updated by multiple individuals working independently at multiple locations. The development of an application based on the ArcIMS and MapObjects platforms was not possible given the time and resource constraints of the current grant and the higher development time that such an application entails.

III. 5. Project Phase II

III. 5. 1. Development of Methodology.

The initial phase of the project focused on determining the best methodology for identifying the matching fragments of shattered glass. This phase of development represented the most challenging aspect of the project and consumed much of the initial months of development. As described in the initial progress report, several approaches were considered and tested to determine their viability for this project and the likelihood that they could be completed within the time and budgetary constraints of the grant.

III. 5. 2. SQL based filtering of joins.

The development path described above (III. 3) focused on an implementation that used an SQL database as its primary means of identifying potential joins. The initial application filtered the database for fragments with complimentary radius measurements and similar attributes.

The collection of radius measurements that represents the most useful attribute gathered during the pre-grant process are generalizations of each side's overall geometry. As noted above, two edges with matching radii may actually contain much different geometric configurations. For example, an edge with a radius of 0.5 m. could represent a feature with a smooth curvature or a feature composed of multiple connecting arcs of slightly different lengths and curvature. The overall radius is simply an approximation of the overall geometry of a particular side. This limitation resulted in multiple matches when SQL queries were run on the dataset.

III. 5. 3. Maximum Likelihood Analysis of SQL Filtered Results.

The second methodology was an extension of the

SQL based strategy just described. This method still relied heavily on data catalogued during the initial pre-grant phase of the project. Potential joins were filtered using SQL queries, and most likely matches were identified and held in memory. Potential sets of matching sides were then incorporated into a Maximum Likelihood Analysis that incorporated several additional attributes. This method drew heavily from multi-spectral image analysis techniques used in the fields of forestry, geography and archaeology. In this type of analysis one or more source elements (also known as training sites in multi-spectral analysis) are used to determine most likely matches from a series of potential matches input into the computer. The source element's attributes define the location of the feature in nth dimensional space with each attribute providing a coordinate value that defines the source element's graphed location. The attributes from the potential matches are similarly plotted in nth dimensional space and their correspondence to the source element is output as a measurement of each element's graphed proximity to the source feature. In other words, the potential match that is closest to the source element within this graph represents the most likely match to the source feature. The application of this method in the present project represents a simplification of this process. Each side has a series of attributes that define the basic form, break pattern, and surface qualities of that piece. In theory, a perfect match would need to have attributes that correspond with those of the source fragment to form a join. The attributes needed for this perfect match defined the source or training site for the classification of the potential joins. The side that clustered nearest to this perfect match would then represent the most likely candidate for the match (Fig. 14).

The catalogued attributes of each shard were reduced to sets of Boolean values in a system of grouping by round numbers and assigning weighting values. Multiple matches still occurred; this, plus the two-step and independent process of database abstraction and visual display for a match assessment, led to a combined approach.

III. 5. 4. Combined Approach: SQL and Shape Indices.

The use of the shard's geometry in the determination of potential matches holds many benefits to understanding how potential matches would join. In theory, when polygons are created

from the fractured edge of each shard, the shape index of that polygon should correspond with the index of a polygon created from the matching edge of the adjacent shard. In most cases, the area and perimeter of a polygon can be used to define an approximate index of the polygon's shape. For example, an ellipse with a perimeter of 5 cm. will have a much different area measurement than a square with a perimeter of 5 cm. In the application tested for this project, a polygon formed from a convex curve in most cases will match a polygon formed from a concave curve if the area and perimeter measurements are comparable.

14. Pane of Glass. Printout of Maximum Likelihood Analysis, SQL filtered results

This methodology was implemented within ArcInfo at the end of the first study session as this platform provided the ability to construct topological relationships for each side of the digitized fragments (Fig. 14). ArcInfo topology uses bounding and co-bounding relationships to compare geometric features with different inherent properties and this feature was vital for developing a geometric comparison of the sides. For example, a line is always bounded by two nodes and has an inherent property of length. Multiple lines bound a polygon, which has the property of area and acquires the property of perimeter from its bounding lines. In this analysis, polygons were created from each side of the test pieces by connecting the beginning and end nodes of the convex and concave curves

allowing comparisons of length, perimeter, and area for each curve. The geometric properties of a source side with a convex curve can then be compared with the geometric properties of sides with concave curves. The intent was to identify sides with similar spatial indices and then to examine the actual fragments in the lab to test the utility of this approach. Initially, this methodology appeared to have significant benefits as it provided a seemingly unbiased account of the relationships of sides.

III. 5 5. GIS Application for a Reconstruction using Database and Geometric/Visual Properties

Given the generalized geometric configurations of the digitized fragments, a decision was made to supplement this approach using the measured properties of each fragment contained in the database. While these measured attributes contain similar biases given the range of interpretations applied to each fragment during the process of cataloguing each piece, the overall wealth of data catalogued offered a wider range of identification criteria than would be possible using only the geometric properties of the digitized fragments. The digitized versions of each piece could then be used to supplement the database and to provide a visual reference when determining most likely joins in the lab.
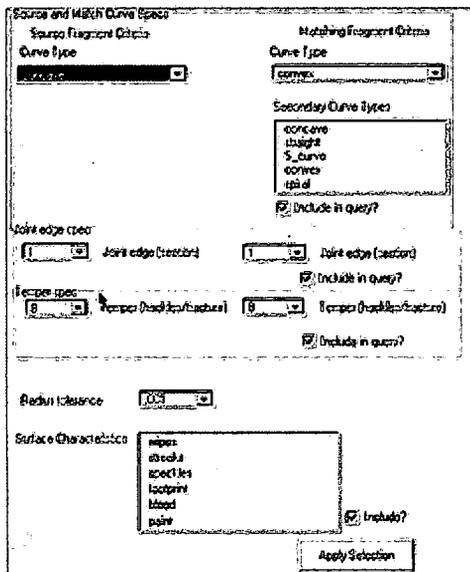

15. ArcView dropdown menu. Choice of filters

An application written in Avenue (a proprietary scripting language for ESRI's ArcView GIS product) was used to provide the research assistants with a quick method for querying and identifying most likely joins. The initial criteria available for each fragment were the radius of each side (offset by a tolerance set by the user), surface characteristics (paint,

streaks from recent cleaning, blood, footprints, speckles and other miscellaneous elements), and curvature type (convex, concave, s-curve, straight edge etc.). A query dialogue provided the assistants with a method for quickly creating complex SQL queries that were assembled and executed through Avenue scripts using the criteria selected by the user (Fig. 15). A subset of potential matches is then created in the attached databases and the most likely list of matches becomes available for subsequent analysis and visual examination.
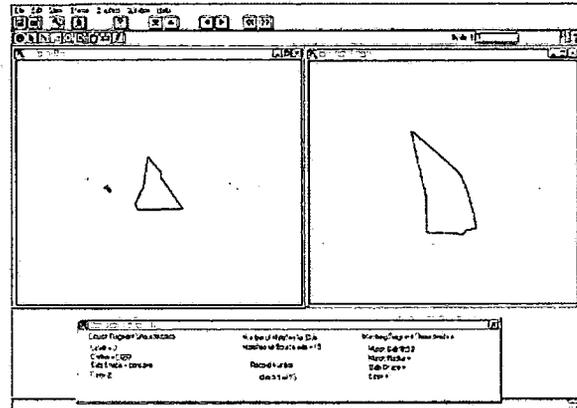
16. ArcView panels. Source shard left, first target shard right
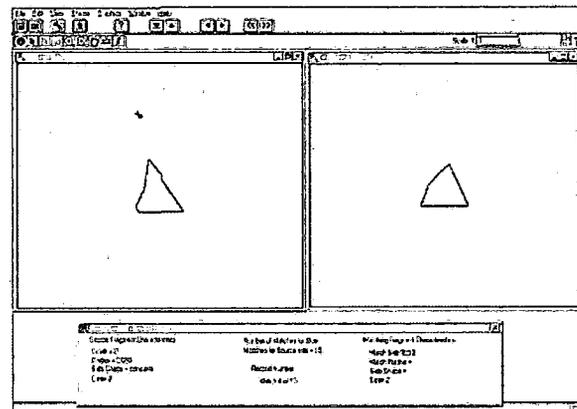
17. ArcView panels. Source shard left, second target shard right

The visual component of this GIS application divides the matches between two windows representing the "source" fragment and its potential match. The "source" fragment is displayed in the window at the left-hand side of the screen and the potential matches are displayed one at a time in the window on the right-hand side (Figs. 16 and 17). A subset of the attributes is then available in a second dialogue at the bottom of the application and additional attributes may be examined by selecting the fragments in either window. The application developed for this project provided the research assistants with the opportunity to

visually inspect each potential match that were subset using the SQL queries and to quickly move back and forth between the matches by clicking forward and back buttons which move through the GIS database displaying the attributes and digitized representation of each potential match. If a match appears to be significantly similar to the source fragment, additional attributes may be quickly brought up and displayed on screen for further scrutiny by the lab assistant (Figs. 18 and 19). An additional benefit to this approach was the ability to quickly view the original laboratory catalogue sheets that contained not only a wealth of information beyond what was appropriate for database entry, but also the photocopy image of the piece itself. These records provide not only references of side and angle characteristics but also a scanned version of the piece itself that was photocopied over a transparency with gridded values that showed not only the actual size of each piece but also the fracture characteristics along each edge (which reproduced very well using this measured scanning technique).

1: Matching Shards - 148		Shape	Polygon	
		Area	0.000253	
		Perimeter	0.068183	
		Fragscl	150	
		Fragscl_id	2464	
		Bar_stor	2A02890	
		Barcde	2A02464	
		Nr_sds	3	
		Wipes	False	
Clear	Clear All			

18. ArcView panels. Dropdown menus for data display

1: Source Shards - 4		Ctr7	0	
		Ctr7_r	0.000	
		Ctr8	0	
		Ctr8_r	0.000	
		Ang1	80	
		Ang2	45	
		Ang3	56	
		Ang4	0	
		Ang5	0	
Clear	Clear All			
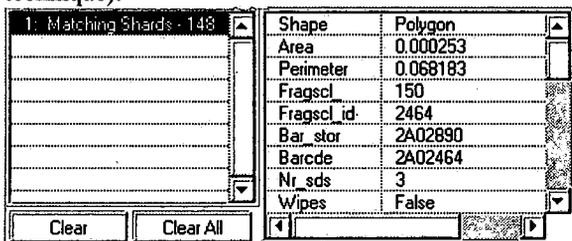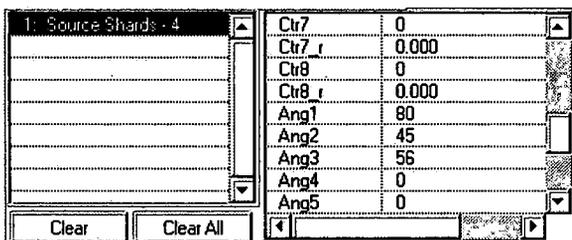
19. ArcView panels. Dropdown menus for data display, contour and inclusive data

IV. Summary

IV. 1. Ground Truth

This methodology was implemented at the University of Minnesota and two research assistants were given directions in its use during a research session in March 2003. The application is installed locally on a laptop within the lab enabling the research assistants to quickly find most likely matches and immediately "ground-truth" these matches by manually examining each join. The application and methodology were constantly refined through the incorporation of additional functionalities to the ArcView scripts. New attributes were added to the list of potential elements used to identify joins. The ability to access the original lab sheets (described above, III. 3) was added during the final months of the project providing additional information about the characteristics of each piece which were not originally captured in the GIS database. The development and refinement of this methodology was an ongoing process that involved continual debugging and enhancements of scripts that were being incorporated into the study as soon as they became available. In many instances, enhancements were in use before they were fully tested and debugged and interaction between developer and researcher necessitated frequent interaction to adequately meet the pace of the final months of the project. Had time permitted, we would have turned to the challenge of scripting the complex SQL query for the matching of compounds of supplementary angles at the intersections of fracture patterns. This approach, at least in theory, would increase the success rate of the reconstruction process.

IV. 2. Results

As this project drew close to the final date of 30 June 2003, the iteration between the programming consultants and the research assistants in the lab reached a point where the number of matches per hour was increasing exponentially, from 1 per hour in the beginning to more than 20 per hour in the final days. The grant period ended before a complete reconstruction of the shattered shards into a pane of glass.

Future prospects for alternative applications arising from the experiments of this project are quite exciting. The project developed a protocol for the reconstruction of a wide variety of shattered, demolished, or dismembered objects besides a pane of glass: buildings, murals, cars, and the like. The methodology and application appeared to be an adequate solution for cataloguing and identifying potential matches. The present approach was kept relatively straightforward and depended upon the storing of multiple and separate versions of each GIS database on the various stations involved in the study and upon having multiple registrations of ArcView 3.3. Research assistants were not able to easily correlate their findings with other members of the team working in different locations and with different versions of the database and application. A better solution, but

one which requires advanced programming, would be to centralize the database and serve the application using either the MapObjects (Java version) or ArcIMS platforms described above.

IV. 3. Future Application Development

Two additional applications (ESRI's MapObjects and IMS platforms) were examined for possible use in future versions of the applications. MapObjects 3.1 from ESRI, was identified as the best package for final application development. MapObjects is a collection of Active X components that provide the functionality of ArcView and much of ArcInfo within Microsoft's Visual Basic development environment. This package would enable the final application to be ported to any Windows-based PC. ArcIMS is an internet-enabled GIS platform that provides many of the functions of ArcView but delivers this functionality through internet or intranet browsers. The application would be maintained within a centralized server and delivered as needed to assistants in the research laboratory or elsewhere. The advantages of this application relate to the centralized storage of the database that can be updated by multiple individuals working independently at multiple locations. The development of an application based on the ArcIMS and MapObjects platforms was not possible given the time and resource constraints of the current grant and the higher development time that such an application entails.

The application and scripts developed for the NIJ project are available online and run on ArcView 3.xxx. Go to clvl.cla.umn.edu\paneglass. However, an anticipated release (2004) of Arc/Info may supplant the aforementioned ESRI specialized modules.

IV. 4. Conclusions

The pilot NIJ project reached a point where it became clear that reconstructions of shattered objects are made possible or can be handled more efficiently by GIS-based computer systems. Developments along these lines accrued in earlier experimentations with the Pylos Fresco and Messene Heroon Projects. There holds promise for further development of GIS application specifically targeted for reconstruction purposes, especially those cases where the number of permutations exceed a practical threshold or where the piecing together depends upon extensive use of intuition and trial and error.

A lesson comes from the three projects.

Fundamental to a successful undertaking is an initial determination of key physical attributes of the pieces, their characterization, and the encoding of the determinates for expedient database entry. Digitizing, even 3D digitizing of the pieces, the scanning of drawings, digital photographs and other computer entry of visual material, represent straightforward operations. The foregoing processes pose no insurmountable obstacle to reconstructions of a whole variety of scattered objects, whether they be forensic or archaeological in nature. Rather, as this undertaking has demonstrated, customization of a preconfigured, user-friendly GIS-system has yet to be obtained, but that goal is within reach.

This NIJ grant report discusses the various protocols which were assessed during the development of a computer-aided system for a potentially wide variety of reconstruction undertakings, whether they be forensic or archaeological in nature. A juxtaposition of the shattered pane of glass on the criminal side against the large body of fresco fragments or temple blocks on the archaeological side clarifies and defines a number of approaches to this kind of problem. Exploded pipe-bombs or aircraft fuselage or large deposits of buried broken pottery or sculpted relief are just a few possibilities for an expanded or a next generation of experimentation, development and refinement.

V. APPENDICES.

V. 1. Appendix A: State of Research on the Pylos Fresco Fragments

A University of Minnesota team investigated in eight seasons, 1991-1998, a Bronze Age Palace at Pylos. The hilltop was occupied primarily from around 1600 B.C.E. to around 1200 B.C.E., or about 3500 years ago. This complex ranks among the best preserved of Bronze Age monuments in Greece. The large palace has yielded clay tablets inscribed in Linear B script, sealings, pottery and a variety of other artifacts, including fragments of decorated fresco wall murals which present a special challenge. More than 4,700 fresco pieces were found scattered over the 10,000 m square area of the site, with a concentration coming from a bronze age mosaic-like floor made of reused painted wall chips. A high percentage are of high-quality, painted in true-fresco technique and bearing elements of figural decoration, a few examples in

Figure 20. In other words, well-worth an

attempt to make joins for larger scenes or at least to determine the number of murals represented. The sheer number makes this ambition an impossibility by traditional methods. Matching joint edges of these fresco fragments is a challenge comparable to the forensic lab's pane of glass.
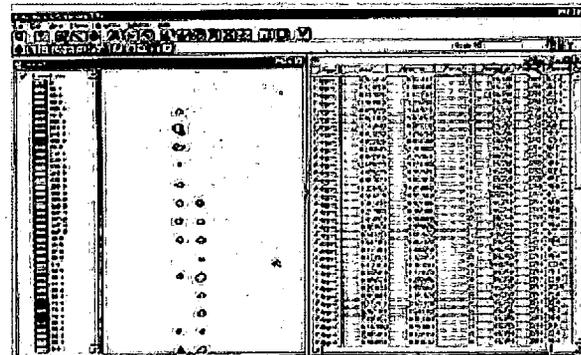

20. Pylos. Trays of Bronze Age fresco fragments

When the quantity of recovered fresco pieces began to exceed the rather finite number which allows for empirical matching and joining, we developed a new method for processing. Each piece was recorded on a standardized inventory sheet with space for a scale drawing and a check list for decorative motifs according to a standardized taxonomy: color according to the Pantone color scale, measurements of height, length, width and thickness, a chart to indicate the width of preserved "stroses," or successive layers of plaster (Fig. 21). This last is an important diagnostic tool because the painted walls at Pylos were prepared by applying two to four preliminary layers of a stucco base. Thicknesses to the successive layers and the composition of the stucco may be consistent according to artistic program but probably varies from project to project. Thus an analysis of the fragment cross-sections is of crucial assistance in assigning pieces to individual scenes on walls. The fragment information was converted to a digital form so that the data can be assessed through a SQL database. This inventory sheet contains 127 fields which are used as filters for recalling sets of painted fragments of common characteristics.
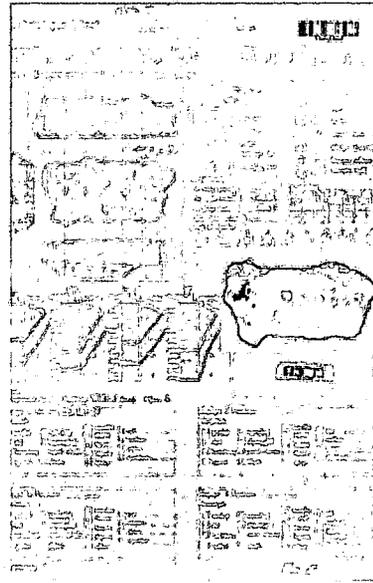
21. Pylos. Typical inventory sheet

The scaled drawing of each piece is digitized into an AutoCAD file and that is transferred and combined with the related database record to ARC/Info. Scanned color photographs of the fragments on the Inventory Sheets not only allow for a viewing of the actual images and colors of the surfaces during the sorting process but also for a multispectral image processing of the painted decorations, separating red, blue, and green bands. This is especially useful in those cases where figural or decorative patterns are difficult to decipher and where image enhancement will clarify the features (Fig. 21). Like the pane of glass project, this procedure permits a computer recall of sets of like fragments for visual analysis and final matching (Fig. 22).

22. Pylos. Fresco fragments aligned in grid

Currently, this aspect of our procedure undergoes development by Frederick Cooper and Todd Brenningmeyer using the experience of the Shattered Object Project. Again, the prospects of success look quite promising.

V. 2. Appendix B: Reconstruction and Design of the Heroon at Messene

A temple-like building formed an indivisible part of the spatial and architectural layout of the stadium complex at the ancient city of Messene. This building (ca. 150 B.C.E) represents one of the most important classical archaeological discoveries in Greece during recent years. It is one of the best survivors of the ancient world. After demolition by vandals in the early medieval period, the Heroon disappeared from view, becoming overgrown with vegetation and overlaid by modern terraces for olive trees. In 1988 the overgrowth was cleared and a trial excavation trench dug. Upon the Heroon's discovery, Professor Themelis asked Cooper to undertake a detailed study for purposes of physical reconstruction and full publication. In two seasons of three weeks each in 1992 and 1993, a team of archaeology students excavated, moved to storage fields, and inventoried a total of 1337 architectural blocks and fragments. We gridded four hectares of storage fields that we laid out according to Universal Traverse Mercator, using the Global Position System (Fig. 23).

23. Messene. Temple blocks organized in fields

The purpose of the medieval vandals had been to rob the iron and lead clamps and dowels. This meant that adjacent blocks, those side by side or above and below one another, would be

excavated and extracted days, if not weeks, apart. Thus, they would be stored in different units in the storage fields. In addition to a fully-dimensioned drawing and photographs of each block, basic information such as find and storage units, height, width, length, and other factual details was entered by student staff onto a database running on handheld computers.

24. Messene. Restored positions of wall blocks in course 2

The podium-Heroon complex contains 34 courses of wall blocks of which 24 courses in the podium-Heroon complex vary in height between 0.210 m. to 1.16 m. The differential course wall heights are coupled with a second architectural feature: a narrowing of wall thickness bottom to top. The two characteristics allow for a database sorting of blocks into separate wall courses (Fig. 24) Other technical and structural details such as clamps and dowels further implement a placement into approximate positions around the perimeter of each course.

25. Messene. Detail of database for inventoried wall blocks

Find spots provided still another variable, all of these variables were entered into a database of 68 fields for manipulation in conjunction with AutoCAD (Fig. 25). The result was a complete

restoration for the Heroon which has 95% of its
blocks preserved, a fact that was unknown and
unexpected at the outset of the project. In
recent seasons, the paper reconstruction was
re-affirmed in the field by temporary
reconstructions of the Heroon's actual wall and
column blocks (Fig. 26).

26. Messene. Reconstruction drawing of W. elevation