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A Digital Approach for Practical Reconstructions of Fragmented Murals

Abstract: Archaeologists and art historians often confront an intractable truth: the near impossibility of piecing together a shattered, fragmented, or disassembled object. Past attempts to reassemble a dismembered monument or valuable work of art involved piecemeal sampling for a hypothetical reconstruction of the object's original appearance. Hundreds or thousands of fragments of a single work surpasses what can be achieved by hands-on trial and error. Today, however, innovative technological advancements of Geographical Information Systems (GIS) and allied computer applications supply the computational power to identify correct joins and allow actual reconstruction of a fragmented art work or ruined architecture. This paper summarizes several successful pilot projects that have as their long-term research goal the development of a computer application which provides an inexpensive, efficient means to catalogue, analyze, and piece together shattered objects and scattered archaeological remains.

Pylos

This paper presents a case study for the use of an integrated computer application for the reassembly of a vast number of scattered fragments from broken fresco wall paintings at Pylos. From 1990 to 1998, the Minnesota Archaeological Researches in the Western Peloponnesos (MARWP) investigated a Bronze Age Palace at Pylos. The hilltop, occupied from around 1600 B.C.E. to around 1200 B.C.E., or about 3500 years ago, ranks among the best preserved of Bronze Age monuments on mainland Greece. During our field seasons, the palace yielded clay tablets inscribed in Linear B script, sealings, pottery and a variety of other artifacts, including a rich quantity of fallen fragments of decorated fresco wall murals *(Fig. 1)*. The site was discovered and originally excavated by Carl Blegen on behalf of the University of Cincinnati from 1952 to 1966. Blegen's excavation was careful, thorough and hugely productive; but in the final publication, the four-volume Palace of Nestor (1966–73), the structural remains were treated as little more than royal and bureaucratic containers for the frescoes, ceramics, sealings, inscriptions and other artifacts that emerged. Despite careful descriptions of the architecture, the walls were never fully documented with state plans, and for the most part only schematic line drawings of rooms, corridors, magazines, courts and other spaces were published (Blegen / Rawson 1966). The Olympia Ephoreia, under whose jurisdiction the palace falls, invited MARWP to systematically expose the palace remains and to document by measured drawings and photographs the details of every wall and floor excavated by Blegen and, in the process, to recover any significant finds from the fill. Our goal in 1990 was to create a stone-by-stone plan of the main palace building (which lies exposed beneath a protective shed roof erected in 1959), and the extensive remains of outlying buildings and features which required re-excavation. The actual state plans provide appropriate documentation for future technical analyses of design and structure for a clearer understanding of the palace and its place in the history of Bronze Age architecture.

In addition to the architectural program, we recovered about 7000 pieces of fresco and painted stucco. Of this amount, 3600 were lotted and discarded because they are battered, undistinguished pieces assessed to be beyond future diagnosis. Most had no more than bits of plaster with flakes of white. The inventoried examples number 3535 and met one or more criterion for catalog entry. Many

Fig. 1. View of Palace at Pylos from SW.

dbase@@/7/97   SCAN

Fresco Catalogue Sheet

Storage Barcode	Locus Barcode
34	

1A03751

Unit Designation:	Locus #:	BAG #	Recorder's Inits:	Date:	Page:
N 120 E 755	4	1	WF	18·07·97	1 of 1

Condition, 1–5 (excellent-poor) ☐4 Condition, desc. *the colors are faded but the design is pretty clear*

Sketch

BACK LEFT RIGHT FRONT

☐ Corner/return
☐ Edge

Shape:
☒ ⬭ oval, hor.
☐ ⬭ oval, vert
☐ ⬠ polygon
☐ ▭ rectangle, hor
☐ ▯ rectangle, vert.

☐ ○ circle
☐ □ square
☐ ◿ triangle, acute
☐ △ triangle, isosceles
☐ ◺ triangle, oblique
☐ ◺ triangle, right

Dimensions:
Ht (max preserv.): .036
Wd (max preserv.): .049
Th (max preserv.): .024
Diam (max preserv.): _____

Photographs

Year	Col Neg		B/W		Slide	
	roll	fr	roll	fr	roll	fr
97	20	22				

SHAPE OF PROFILE
1 2 3 4 5 6 7 8 9 10

front	right	back	left
SHAPE ☒ SURFACE	SHAPE ☒ SURFACE	SHAPE ☐ SURFACE	SHAPE ☒ SURFACE

Sirosis

.005 .010 .015 .020 .025 .030 .035 .040

Decoration:
 Background color: Pantone: 18-9

Design 1: Pantone: 325-2
Descript:
☐ arc(s) ☒ band(s) ☐ rosette ☒ wd: 002
☐ dot ☐ zigzag(s) ☐ floral ☐ radius: ___
☐ hatching ☐ semi-circle ☐ fauna ☒ diam: 015
☒ spiral ☐ circle ☐ figure ☐ number: ___
        ☐ other:

Design 2: Pantone: 325-2
Descript: *dips into D6 near right edge*
☐ arc(s) ☒ band(s) ☐ rosette ☒ wd: 0015
☐ dot ☐ zigzag(s) ☐ floral ☐ radius: ___
☐ hatching ☐ semi-circle ☐ fauna ☐ diam: ___
☐ spiral ☐ circle ☐ figure ☐ number: ___
        ☐ other:

Design 3: Pantone: 66-1
Descript: *faded w/ deposits*
☐ arc(s) ☒ band(s) ☐ rosette ☒ wd: 006
☐ dot ☐ zigzag(s) ☐ floral ☐ radius: ___
☐ hatching ☐ semi-circle ☐ fauna ☐ diam: ___
☐ spiral ☐ circle ☐ figure ☐ number: ___
        ☐ other:

Design 4 Pantone: 325-2
Descript:
☐ arc(s) ☐ band(s) ☐ rosette ☒ wd: 002
☐ dot ☐ zigzag(s) ☐ floral ☐ radius: ___
☒ hatching ☐ semi-circle ☐ fauna ☐ diam: ___
☐ spiral ☐ circle ☐ figure ☐ number: ___
        ☐ other:

Comments: *Indentation of 1/2 circle cylinder on back; many of the colors are blended.*

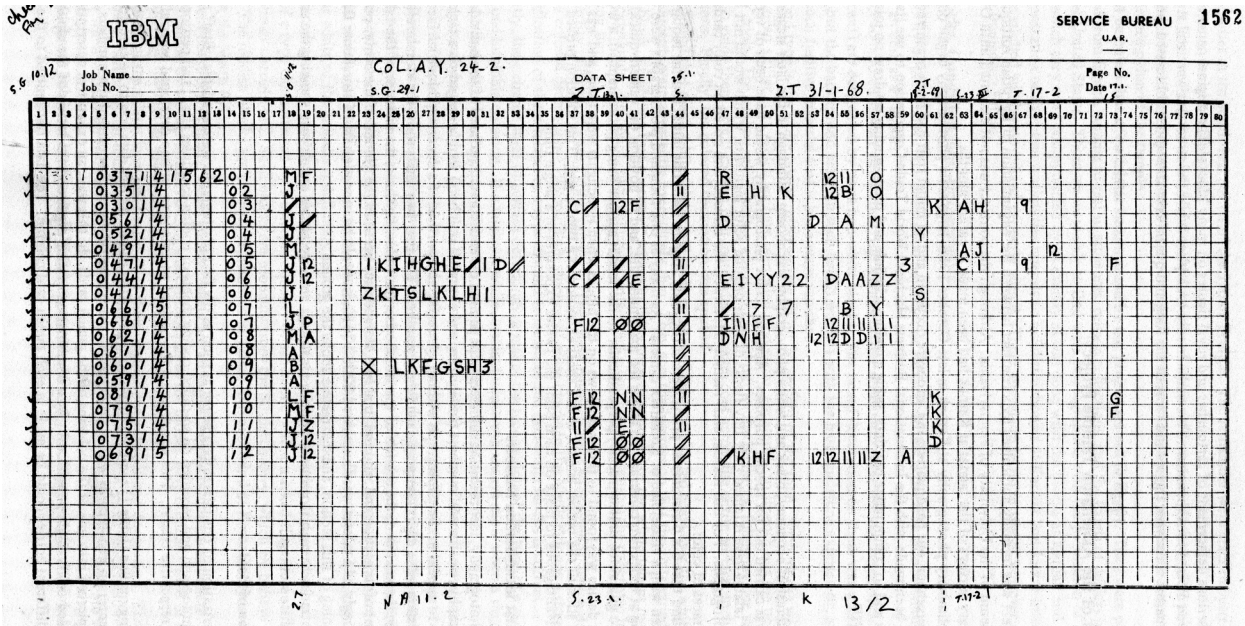Fig. 2. Fresco inventory sheet with photo and barcode for 1A0375.

Fig. 3. The Akhenaten Temple Project, sample encoding sheet (Smith/Redford 1976, Fig. 1).

had distinguishing features including multiple colors and patterns *(Fig. 2)*. Nearly all are relatively small; they average in size 30 by 30 millimeters. No adjoining pieces were found in situ. The challenge in this case, as in the others described herein, is to devise a recording protocol which maximizes a computer application in order to achieve a reconstruction more efficiently than one undertaken manually.

The Pylos Project is one of three archaeological expeditions undertaken by MARWP in which computer applications played a prominent role. Besides The Bronze Age Palace at Pylos (1990–1998), there are The Morea Vernacular Architecture Survey (1991–2000), published in 2002, and The Reconstruction of a Hellenistic Temple at Messene (1991 to present). An on line and interactive access to the Morea data is published elsewhere in the CAA 2007 Proceedings (Brenningmeyer / Cooper / Downey 1998; Cooper 2002). A forerunner to the computer application discussed in this paper led to plans and elevations for an actual reconstruction of the architectural remains at Messene (Cooper 1999).

The Akhenaten Temple Project

From the earliest days of computers, archaeologists dreamed of the assistance that this technology might provide, but have met with dead ends along the way

because of a general misunderstanding of what can be assigned to computer productivity and should not. Beginning in the 1960s and continuing pretty much to today, archaeologists have had a strong preference for note-taking for narrative description, often detailed and unnecessarily extensive. This approach is antithetical to the hex/byte table available to computer data entry. All too many archaeologists continue to favor text over an encoded format for computer entry. A pioneer project, the inspiration for the approach taken in the various MARWP endeavors, is the Akhenaten Temple Project where over 35,000 blocks from temples built by Akhenaten were demolished by his XVIII dynasty successors and reused in pylons and gateways. The majority of these small (0.52 m × 0.22 m × 0.26 m) sandstone blocks, called talatat, bear decorated surfaces from large, originally painted scenes in raised relief and in bas-relief (Smith / Redford 1976, ix). The project for reconstruction of the scenes began in 1966 as a collaboration between the University of Pennsylvania and the Cairo office of IBM. In those days, sheets were filled out by hand, transferred to punch-cards which were then processed by a customized program *(Fig. 3)*. The approach to computer processing data was based entirely on the encoding of not only metrical attributes such as angles between the converging rays of sun but also other types of configurations such as human figures, their postures and other attributes: ones that passed across one talatat to another *(Fig. 4)*.
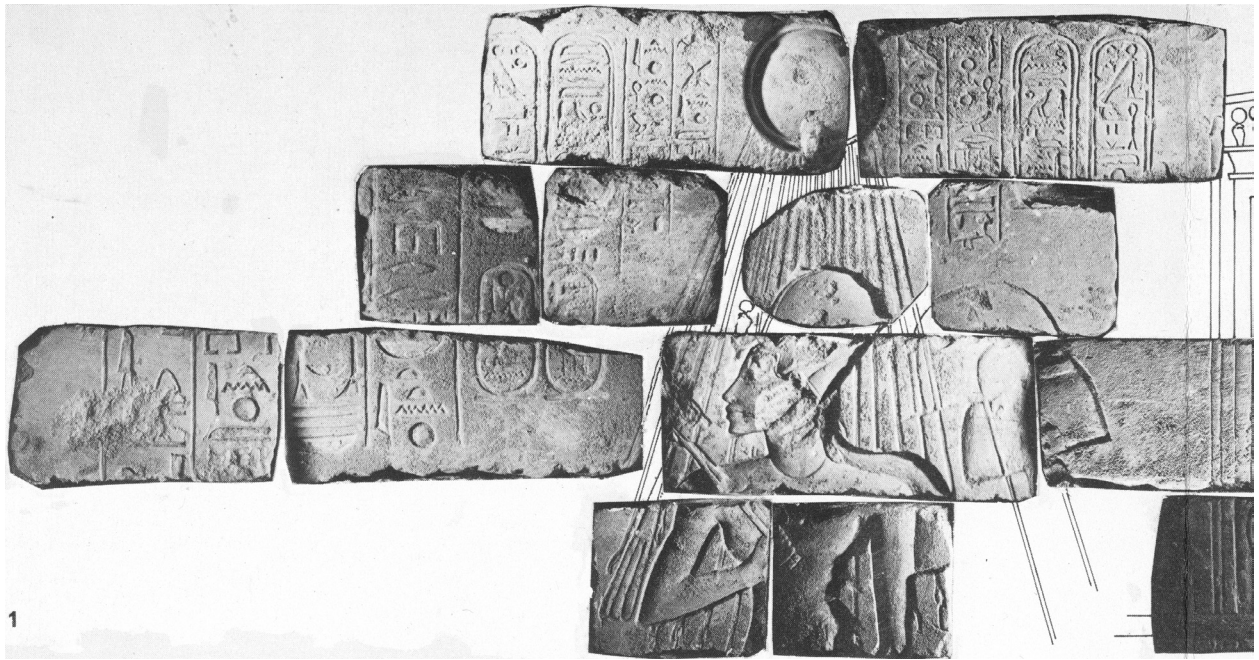
Fig. 4. The Akhenaten Temple Project, House of the Disk, procession of King and Queen (Smith/Redford 1976, pl. 8,1).

In an introductory chapter of Volume I: The Akhenaten Temple Project, the Initial Discoveries, Ray Winfield Smith, director from 1966 to 1972, advances a set of procedures that allowed for the optimal use of the "electronic computer" to sort and greatly assist in the previously impossible ambition of matching joins for the 35,000 extant talatat. The advantages of the mainframe were many but there were constraints, not the least of which was the entry of narrative description. This limitation led to a careful selection of attributes so that computer entries contained only encoded and critical information applicable to all talatat and potentially useful for grouping the talatat into scenes. All this data had to be reduced to an encoded letter. Each punch card had 80 columns and 39 allowable entries for each column (Smith / Redford 1976, 9). The permissible characters were single letters of the alphabet, A–Z, single numbers, 0–9, and 3 symbols, + – /. The team developed an encoded schedule whereby kinds of pictorial figures, for example kings as // or kneeling man as 1, were written on a paper encoding sheet and then keyed onto the punch cards that were fed into the mainframe. Measurements were reduced to encoded alphabetic letters. Ray-lines emanate from the divine sun-disk at a maximum obtuse angle of 100 degrees; angle measurements, however, were taken from the horizontal joint to the respective deflections on the right or left hand lines of rays. By fortunate necessity, the 100 degrees was divided into 4 degree increments and assigned a letter. This margin was reduced by an ingenious coupling of letters which could be reversed in adjacent columns, FG in columns 27 and 28 indicates 104 to 107 degrees, with a reversal, GF meaning it falls within the lower range, 104 to 105 degrees, and so forth (pp. 9–12). Instead of reducing accuracy, this encoding eliminated false precision, an inevitable variability of values read from a protractor of single ray lines that pass across adjoining stretchers and headers.

Another important feature of the Akhenaten Temple Project computer protocol was the assignment of a unique inventory number based on a Cartesian coordinate system of x, y, and z values, giving the position within a tenth of a meter for each talatat in the storage area. In this respect, the project managers recognized a major handicap: the find spots for 90% of the talatat went unrecorded when removed from the modern day demolishing of pylons and gateways. Secondary locations, if known, would be valuable clues to help in a reassembly of blocks for whole scenes and for the identification of the original monument. The 35,000 talatat were packed into storage in no particular order and virtually unmovable. This meant that photographs became the primary vehicle for reconstruction. A large format Hasselblad negative (9 × 12 cm) was taken of each block.

Photographic prints became the visual and manual means to verify joins sorted by the mainframe computer and printed into volumes divided by subject. This is another important lesson in computer-assisted reconstruction. In the process of assembling provisional or temporary scenes, photographs are constantly on the move, shifting from one trial scene to an alternative. This makes tracking past and current positions of each talatat a necessity, like FedEx does with packages. It is expected that future excavation and clearing of additional talatat will add to the current base of 35,000; the computer magnetic tapes allow this to be an on-going enterprise. The authors of the Akhenaten Temple Project were prescient to suggest, "The use of computers in this project is on a novel basis, which is likely to be adopted with modifications elsewhere in archaeological problems. Basically, our decision to use computers reflected the recognition that a project of this magnitude should never be attempted otherwise" (Smith / Redford 1976, 7). The second point is by all means correct; the point made in the first sentence has yet to catch on, except for our archaeological undertakings and the later MARWP projects, as far as we are aware.

The following lists some of the rules we extrapolated from the Akhenaten Temple Project and have continued to use to develop computer-aided assistance in a sequence of reconstruction projects.

1. Determine physical characteristics which form common denominators across groups of objects.
2. Basic information trumps "sophisticated details".
3. Develop an encoding sheet for hand-written entry, organized to facilitate computer database entry.
4. Adopt metrical attributes.
5. Encode measurements to allow for the range of readings that invariably occur for a given value.
6. Know the difference between accuracy and precision; avoid false precision.
7. Always design an inventory system that uses unique numbers for each object (finds and photos).
8. Define a database structure that gives priority to field types: Logical, Numeric and, lastly, Character.
9. Design a database structure that allows for continued and future application.
10. Use a site-based Cartesian coordinate system for every possible attribute. Nowadays, use GPS and UTM.
11. Assume that computer sorting yields a selection of possible joins, never an absolute one.
12. Comparison of photographs (digital images) is an optimal method for ground-truthing tentative matches.
13. Track all objects from origin, to sort tables, to stored location, to current location (we use barcode technology).
14. Balance a trade-off between small projects best done manually against projects of "magnitude" that can only be achieved by computer processing.
15. Do not start at zero, assess earlier and appropriate developments in computer applications for reconstruction.

The emergence in the early 1980s of the Hewlett Packard handheld computer, the HP 41CV, along with successive model improvements, made it economical to have in the field multiple and rugged units for the trench-side and user-friendly entry of data. A flat-file database engine for the HP CV 48, released in 1992, incorporated a portal for an unencumbered downloading of the data to a PC (Donnelly 1992).

The Pylos Fresco

The computer-aided joining of the Pylos fresco fragments is complicated by a problem of a mixed provenance. The fresco material divides into four types of find spots. First: the main palace as well as a smaller palace located alongside and to the southwest of the first (Lang 1950; McCallum 1987). Second: deposit made in the Bronze Age at the Northwest slope under a wild olive tree. Third and fourth: those fresco fragments discovered by MARWP. The third MARWP find spot is from a mosaic-chip floor at the Northeast and the fourth category includes those found in trenches spread over the site. Only within the confines of the palaces, Blegen was scrupulous in noting positions of all significant pieces of fresco.

Blegen's excavation protocol was common procedure. He laid out various-sized trenches as excavation progressed, moving from a finished area to an adjacent one. Finds were extracted when encountered, kept artifacts were set aside in trays, and the discarded went into a separate pile at the trench edge. At the end of each season, workmen spread the excavated earth over each trench as a protective back-fill. Notebooks emphasized descriptive strati-

graphy within a given trench; elevations relative to a benchmark were rare. Only in special circumstances or with raised expectations did Blegen sift excavated fill.

Fresco fragments from the second find spot were discarded back in the Bronze Age, sometime before the construction of the Late Mycenaean palace. In 1960, tourists visiting the site began scavenging painted fresco pieces from a steep scarp, then held in place by a wild olive tree. The deposit contained almost 3000 fragments, of which only 28 examples were published (Lang 1969). The excavation and object inventory data have been uploaded from the flat-file databases to a more robust SQL database having multiple and linked tables. Simple and multi-level queries are extracted and sorted into batches of kindred fresco fragments based on find-spot and any number of choices from the recorded attributes *(Fig. 2)*. We began with MySQL, but recently decided to move to PostgresSQL; the reason is explained later.

Figure 5 marks in bold type the distribution by quantities of fresco pieces included in Mabel Lang's catalog. It is obvious that the selection was pulled almost entirely from the confines of the palace. The distribution map from the MARWP excavations shows a different distribution picture altogether: frescoes, or rather fragments of wall paintings, surround the royal quarters and come from the ancillary buildings as well. The evidence of the plan belies Lang's assumption that figurative wall paintings were confined to the royal domain and that murals were inappropriate to the function of ancillary buildings which he identified as workshops, wine magazines and the like *(Fig. 6)*. We make this point because we, too, had assumed that wall paintings
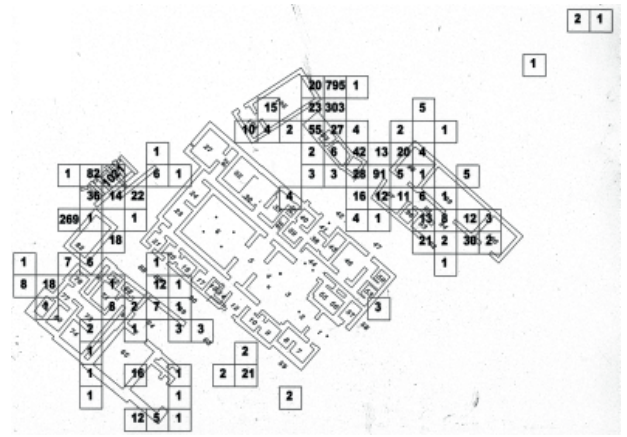

Fig. 6. Palace at Pylos, distribution of quantities of fresco, MARWP excavations, by unit.

at Pylos were the provenance of the two royal residences, the main palace and the Southwest Palace. We are sympathetic to Lang's bewilderment at the sheer quantity of recovered fragments from the formidable Bronze Age deposit under the wild-olive tree discard deposit dump. We also discovered a compacted floor, laid as a mosaic pavement, composed of at least two to five layers of wall fresco chips, lying painted side up for the most part, ranging in surface area and depth from approximately 5 to 50 millimeters square. The 1142 fragments appear to have come from a wall decorated with geometric patterns, including terracotta-colored spirals on an ocher background, and red-and-white stripes; there is some indication of floral designs and perhaps some miniature human figures. The stratigraphic context of the floor predates the palace by several building periods, or by at least one-hundred years.

Northwest Dump of Excavated and Discarded Finds

Along the Northwest edge of the acropolis, Blegen's staff excavated a deep and multi-period profusion of walls. No sense could be made of them. At the close of excavations in 1965, the deep cavities within the grillage of walls were filled by excavation discard described above. The MARWP project excavated Blegen's dump and removed three hundred and sixty-five olive sacks, totaling about 20 tons or approximately 2,250,000 artifacts consisting of pottery, roof tiles, stone tools, painted fresco fragments, and Linear B tablets. While this material lacks all context, it does provide an index and a range of typical

Fig. 5. Palace at Pylos, distribution of quantities of fresco from Lang 1969.

artifacts and their relative quantities. The material also gives an idea of the chronological span of activity on the akropolis. We expedited the tedium and long hours of sorting and inspection of this material by a hand-operated conveyor belt. This allowed us to inspect in passing every artifact coming from the Blegen dump. Every object of interest or meeting the specifications named above was pulled from the conveyor belt for processing. The retrieved painted stucco and fresco pieces principally come from only two contiguous loci in a single MARWP unit within the Northwest cavity.

The MARWP Computer-Aided Excavation Protocol

At the offset in 1991, MARWP adopted an excavation protocol on the availability not only of computer database registration, but also on GPS and bar code systems. An excavation grid of 5 x 5 m trenches based on the UTM coordinate system was fixed over the site and benchmarks were established based on the UTM geoid datum. Each unit was excavated deposit by deposit, horizontally and vertically, the sub-component being referred to as a locus. All recovered objects can be assigned a three-dimensional coordinate. Kept objects were each recorded on separate finds sheets, designed to emphasize physical, especially metrological characteristics common to a given class, that is, an updated variation on the Akhenaten Talatat Project mentioned above.

The Fresco Pieces Specifically

The fresco sheet sets aside a space for a scale drawing and the rest of the sheet is dedicated to a check list for decorative motifs according to a standardized taxonomy: color according to the Pantone color scale (as opposed to text descriptions such as "pinkish-azure"), measurements of height, length, width and thickness, a chart to indicate the width of preserved "stroses", or successive layers of plaster *(Fig. 2)*. This last is an important diagnostic tool because the painted walls at Pylos were prepared by applying one to four preliminary layers of a stucco base before the final, thin surface coating which received the colors. Thicknesses of the successive layers and the composition of the stucco may be consistent according to artistic program, but probably vary from project to project. Thus an analysis of the fragment cross-sections is of crucial assistance in assigning pieces to individual scenes on walls (Pappa-

lalardo 1998–2000). 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 used as filters for recalling sets of painted fragments of common characteristics.

Use of Bar Codes

As part of the early computerization of MARWP projects, we adopted bar code technology. As in the commercial world, the use of bar codes dramatically increases efficiencies in the labeling of objects, tracking the movement of objects, the reduction of human error in database entry, and so forth. A bar code inventory number was assigned and attached to each object, a reserve label placed in the storage tray and a third attached to the inventory sheet. The bar code label appears in the photographs and also serves as a scale. Incidentally, the bar codes in the photographs can be read by a scanner wand. The quantified information on each sheet was entered as a record into the database. The paper sheets and color negatives are in the process of being scanned. This means that any object or whole classes of objects can be retrieved by a formulation of a SQL query and mapped electronically.

On-going Computer Technology

We despaired, as did Mabel Lang before us, at any prospect for establishing coherency, given the large volume of small and varied pieces recovered during our investigations. However, we believed that a digital and therefore widely accessible method to document, query and examine fragments of the Pylos murals would be of great scholarly interest. Beginning in 1997, and continuing intermittently since, Cooper and Brenningmeyer have addressed the potential of computer applications in the study of these fresco pieces. We began by considering the attributes and geometric properties of the fragments as elements that together uniquely describe each piece. As noted above, scaled drawings and photographs provided two-dimensional plan views of each fragment with the third dimension preserved through profile drawings and "stroses" measurements. Additional data extracted from the inventory sheets provided detailed attributes describing Pantone colors and related measurements and observations for each fragment. Taken together the geomet-

ric and attribute data were perfectly suited to a GIS application. For reasons not elaborated here, we did not turn to the options of 3D modeling and simulation; development of a GIS based system fits our project needs.

Several members of the MARWP team were proficient in AutoCAD, which was used in the digitization of each scaled drawing. An arbitrary coordinate system was developed to position each fragment within a two-dimensional coordinate space, thereby preserving the objects' dimensions as measured within the graphical display. The digitized Auto-CAD files were digitized within this arbitrary coordinate frame and exported to an Arc/Info coverage where the geometry was tied to its related attributes. Topological relationships were constructed within Arc/Info, which provided tools for assuring and correcting the constructed topologies. The fresco GIS application as originally conceived and developed within Arc/Info enabled MARWP researchers to quickly query fragments based on attributes of interest and display fragments with comparable measurements for comparison on-screen. The coordinate space that bound each fragment ensured uniform display scales across views. The use of vectorized and topologically aware objects in this application also presented opportunities for geometrically based queries.

In a related project (Cooper / Brenningmeyer 2005), we experimented with the use of shape indices to determine most likely matches for shattered fragments of glass. While the exact approach used in the glass reconstruction is unlikely to work with the battered fresco remains, the opportunity to use geometric characteristics, including shape indices describing digitized polygons of interior decorative elements may be of some use in later operations. The Pylos fresco application was ported to ESRI's ArcView product which provided a more intuitive graphical interface for users. Additional objects were tied to the fresco database including scanned images of the original inventory sheets and color photographs of each fragment. Users could quickly query the database for attributes of interest and examine the original scaled drawings and photographs taken during conservation operations. The option to quickly review scans of the original sheets and photographs is especially useful in those cases where figural or decorative patterns are difficult to decipher and where image enhancement will clarify features obscured in the digitization process.

While this initial GIS based approach provided a robust yet simple method to sort, query and examine fragments of interest, there were a number of limitations that were encountered. Fragments within this application exist in a static coordinate frame and although it is possible to view fragments separated within this coordinate space using separate viewers it is difficult to efficiently move, rotate and connect related objects on-screen. Likewise, the application was developed as a desktop application and therefore has been used by a limited number of individuals. In the next stage, our intention is to build on and tie together the ambitious and successful models developed in this and other MARWP projects. Our goal is to maintain many of the qualities of the desktop application but to port these to a web-based model developed with Open Source technologies. Within the application a separate "sorting screen" is available to display images of selected fragments within a browser window. Each image is embedded within a Cascading Style Sheet (CSS) container which will enable screen sorting and rotate capabilities that mimic the physical sorting tray used in the laboratory or field. Ajax based scripts will enhance the speed of these sorting operations. Similar Ajax based applications are currently used to sort, categorize and query image databases and our application will use ideas that are comparable to those currently available. The Prototype JavaScript framework (http://prototypejs.org/) is used to ensure cross platform compatibility and the JavaScript library at http://script.aculo.us provides access to a user interface with many of the sort and query functions that form the core of the Pylos fresco program. The GIS query capabilities will be maintained through the use of PostGIS (a module within PostgresSQL) and the University of Minnesota's MapServer application which provide many of the same query capabilities as the desktop application but offer much wider access to these tools than is currently available (Mathew / Stones 2005; Kropla 2005). The fresco database has link ids that connect the fragment to its locus and UTM location within the site and it will be possible to connect the fresco and excavation datasets through the MARWP MapServer application described elsewhere in this volume. The tools, scripts and various components of the MARWP Internet GIS are based on Open Source models.

The goal of our ongoing work is to continue the development of a user-friendly, broadly-adaptable, and open source template for the reconstruction of shattered objects in excavations and other contexts.

The open architecture is to be designed to encourage collaboration among researchers and rapid dissemination of results and archaeological data.

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