PHOTOGRAMMETRIC STRUCTURED DATA ACQUISITION AND COMPRESSION AIMED TO STATIC ANALYSIS BY FINITE ELEMENTS METHODS - A TEST ON THE COLOSSEO

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ABSTRACT

Of the current survey operations on the Colosseo, photogrammetry of the face is undoubtedly one of the most urgent preliminary stages in filling the gaps in basic documentation which have hitherto hindered the studies and analyses required for adequate protection of the monument. This note describes the results from a specific photogrammetric data acquisition procedure which takes account of the subsequent specific data processing operations. This procedure uses a plotting instrument and contemporaneous restructuring of the data into categories which are also topologically defined. The data are thinned to extract coordinates of characteristic points for definition of a correct basic geometry for input to structure evaluation programs using the method of finite elements.

Key Words: Data Compression, Architectural Photogrammetry, Structural Analisys

1. INTRODUCTION

In general, the use of photogrammetry for surveying architectural structures may produce different results according to the quality and quantity of the elements plotted.
This is due to dependence on subjective interpretation of the photographs (present even when 3D stereoscope vision is used), and is also related to the multiplicity of meanings given to the word "survey".
In our case, we tackled the requirement stated by structure experts for automatic processing of often excessive photogrammetry data to create a model more suitable for finite element calculation.
An attempt was also made to create a hierarchical structure for the data that would permit automatic generation of surfaces for computer graphics display.

2. GENERAL APPROACH TO PHOTOGRAMMETRY

The Colosseo survey (Birardi et Al., 1987; Carlucci, 1989) was started in 1987 by the "Topografia e Geodesia" section of the "Dipartimento di Idraulica, Trasporti e Strade" of the "La Sapienza" University of Rome.
The photos covered the entire external face and were taken on 4x5 inches color slides with 99.66 mm focal length and a mean scale of 1:300, suitable for restitution up to scale 1:50.
The control points on the monument were determined by the vertexes of a general topographical grid and were situated one for every two columns for the first three levels, less closely for the attic.
The r.m.s. obtained in compensation for each X and Y coordinate did not exceed 2 mm. Heights were derived from the mean of all the zenithal measurements.
The coordinates of the control points were, as stated, calculated in a reference system external to the monument (and linked to the national system). To make plotting of the sample model possible (the axes of the plotting instrument reference system do not correspond to those of the external reference system), a local (orthogonal cartesian) system of coordinates was devised effecting a rotary-translation in such a way as to have one axis parallel to the straight line joining two successive control points on the external wall (and the origin at the first of them). A subsequent inverse rotary-translation makes it possible to bring each point measured into the original general reference system.
The pair of photograms was oriented absolutely on the control points referred to the aforesaid "local system", and the residuals for the three coordinates of each point resulting from calculation of the parameters of absolute orientation of the model were less than 2 mm.
The application presented is limited to a portion of the external wall of the Colosseo, specifically the ground level arch with the Roman numeral XLII carved on the travertine.
Plotting was effected using the pair formed by photograms 15a and 16a and performed with the Digicart40 analytic plotter from Galileo Siscam.
Specific attention was given to the 3D aspect of the analytical numerical restitution so as to produce a truly 3D model (Figures 1 and 2).

3. 3D DATA ACQUISITION

In previous research on restitution of the external wall of the Colosseo, the need for complete knowledge of the monument resulted in care being taken not to overemphasize any particular aspect. This resulted in plotting (as far as possible on the scale chosen for the final graphics product) of not only all the geometrical and architectural lines of the monument including those describing its masonry structure, but also the deformation and breakages in these lines caused by deterioration.

The greatest difficulties in rendering the wall are in fact encountered in tracing the parts affected by severe erosion and decomposition of the material, which have led to the disappearance of well defined lines and angles. In such previous research only the lines that presently exist were plotted with interruptions where they ocurred, and attempts were always made to trace the lines of delimitation (if visible) between the solid (pillar) and void (arch).

In spite of the fact that there was a requirement to adopt a restitution system as far as possible not designed only for specific needs, the work and coding were performed in such a way as to make it possible to create maps on specific topics to meet the need different needs of future projects for the monument or simply those of recording its state at the time of the survey.

The restitution codes used were designed to be representative of a group of characteristics of the object, such as, for example, geometrical, structural or style features, materials, deterioration and restoration. Exact knowledge of the various types of processing required by all those interested in the monument was the basis for proper planning of code selection.

However restitution performed with such operating criteria proved still to be inadequate for computer graphics processing that uses photogrammetric data to define a 3D geometrical model displayed by solid modelling techniques.

To define an object three-dimensionally, it is not sufficient to represent its vertexes and corners. It is also necessary to define the individual surfaces which together delimit the solid.

The limitation imposed by having to illustrate three dimensional objects in two dimensions is thus evident.

The present study was aimed particularly at the realistic restitution of the data acquired. A different type of data acquisition was therefore implemented. Instead of points belonging to segments which - in orthogonal projections like the classical restitution product - generally represent the visual outlines of the various elements making up the object, points were acquired situated on the lines that represent the borders of the surfaces that will later be reconstructed.

Each individual surface must therefore be plotted as a closed polylineal that represents its outline. From analysis of the monument, the basic closed constructional entity was identified as the outline of the single quoin of travertine, defined by a line that completes a closed cycle and therefore delimits a surface. Within each quoin one can identify other surfaces that characterize it (holes, architectural decorations etc. and which are plotted as such, but also open lines (which for the most part indicate lesions) and most importantly a certain number of isolated points necessary for definition of ondulations of the surfaces, the number of which depends on the extent to which it is "humped".

With the techniques of triangulation or modelling with interpolant surfaces, these data are then processed to reconstruct the faces of the object (Del Bufalo et Al., 1988).

In view of the small size of the portion of monument plotted an extended code for the restitution data was not used, instead a restricted number of codes representative of its characteristics were chosen.

Table 1 contains the list of the rendering codes.

PERCONCI	01	0	Perimetro del concio	3DPLINE
INTCONCI	02	0	Punto interno al concio	3DPOINT
LINEAINT	03	0	Linea interna al concio	3DPLINE open
PERIFORI	04	0	Perimetro di fori o crepe	3DPLINE closed
INTEFORI	05	0	Punto interno al foro o alla crepa	3DPOINT
BASECOLO	06	0	Base della colonna	3DPLINE closed
PCOLONNA	07	0	Profilo del fusto della colonna	3DPLINE open
CAPITELL	08	0	Capitello della colonna	3DPLINE closed
CIMPOSTA	09	0	Cornice di imposta dell'arco	3DPLINE closed
ARCHIVOL	10	0	Archivolto	3DPLINE closed
NUMERARC	11	0	Numerazione romana dell'arco	3DPLINE closed
PTOAPPOG	12	0	Punto topografico d'appoggio	3DPOINT

TABLE 1 : Rendering Codes

From the point of view of numerical graphics, the elements were divided into three categories:

3DPOINT Points defined with three coordinates;

3DPOLY Three dimensional polylineal, generally closed;

3DFACE Three dimensional surfaces of which the edges and characteristic points are defined. In this case successive automatic processings make it possible to perform either polynomial approximation to define the trend of the surface equation, or identify plane triangles to create triangulated structures with successive approximation for the final computerized display.

The first code described (PERCONCI) is the basic one that identifies the points on the border of the basic unit, while the second (INTCONCI) codes the points with heights within the quoin.
The other surfaces identified within the quoin were then, as already stated, plotted as closed and coded polylineals, taking account of the different style or constructional characteristics of the portion of monument examined.
To complete the restitution phase, the operation of graphics data editing, managed by the same software that manages the plotter (MACROS), becomes particularly useful if one works with the restitution system described above.
It is possible to perform a whole series of operations on the unit (partial or total cancellation, displacement of vertices, construction of a unit connecting isolated points and so on) which are often necessary for correction of errors or to make up for the inevitable omissions in the restitution phase. A typical example is the construction (made mandatory in editing) of the unit referring to the lateral surfaces of the architectural decorations, obtaining by joining single points belonging to different planes.
At the end of these operations one obtains an ASCII file of coordinates which forms the starting point for subsequent processing.

4. DATA THINNING.

The research also revealed the importance of defining modalities of distribution and appropiate density for points acquired, in order to achieve the best ratio between amount of data and closeness to reality, according to the scale of restitution desired. The question becomes particularly important in architectural work, in which a wrong density could lead to definition of lines differing from the real ones, with all the consequences that would be entailed in both historical interpretation and analysis of statics. Too low a density of points, for example, could be counteracted by execution of a subsequent spline, with a definition of curvatures that might be completely different from the original. Attention must therefore be given to the acquisition phase, ensuring that it is compatible with a possible subsequent thinning operation. In our research various techniques have been used, which are described briefly below, and methods that can be extended to most cases have been tested.

4.1 Recording systems

The ordinary acquisition systems used in numerical plotters, based on various types of real-time recording (single point, space increment, time increment, mixed space and time, vector) involve different modalities to which there correspond differing amounts of data recorded for the same object. Problems of memory occupation apart, these may also generate differeing approximations to reality, depending on both the algorithm and the increments imposed by the operator. Even when working on the same object, it is therefore easy to produce totally non-homogeneous configurations of data amounts and approximations.
Hence the need for a procedure to check and where necessary thin, one that will make it possible to store data corresponding to the characteristics of the object and to specific prescriptions, in a way fully analogous to acquisition of non-photographer 2D data, such as digitalization of existing graphics. In the restitution performed, a vector recording system with 5 gon increments was used. It is interesting to analyze the methods developed for automatic line generation in changing the scale of maps. Researches in the field of pattern generation, image processing and computer vision is particularly concerned with the problems of detecting corners, and its findings are studied for application in problems of digitalized data compression. In our case such research can be adapted to the problem of finding the principal angles to insert in the approximate geometry of finite element calculation.
A method proposed in 1988 (Thapa, 1988) "zero crossing algorithm" identifies the critical points to record for different degrees of generalization due to the change of scale. Application of this algorithm, however, is laborious, as it requires an initial transformation from vector to raster form (for example by the Bresenham algorithm (Bresenham, 1965)) and a subsequent filter type analysis to reduce noise. Perhaps more interesting for our purpose is the CVD algorithm (Commutator Vertex Detection, detection of vertexes by commutating operators) by Anderson and Bezdeck in 1984 (Anderson et Al., 1984).
This was tried by Thapa (Thapa, 1990) and adapted to problems of compressing data

for digitalized lines. This method meets the requirement for subsequent data thinning, which makes it possible to examine a file of data plotted and extract only those necessary, eliminating the excess. The specific interest of this algorithm lies in the possibility of thinning to a density that can be varied and set according to the type of final result desired. In fact the thinning rate can be set anywhere between a barely perceptible minimum and a maximum at which only the critical points are recorded: vertexes of the elementary polygons that identify the object, which in a curved line are points of high curvature, intersections, and the start and end of the line.

4.2 Anderson and Bezdeck's CVD algorithm

The basis of the theory developed by Anderson and Bezdeck is to search in the statistical and geometrical properties associated with the structure for eigenvalues and eigenvectors of a typical covariance matrix.

The problem can be put as follows:

1. If one considers a sample of points

$$P = (p_1, p_2, \dots p_n)$$

defined in R2 where

$$p_i = \begin{pmatrix} x_i \\ y_i \end{pmatrix}$$

2. Given the characteristic mean vector

$$v_p = \sum_{i=1}^{n} p_i / n$$

and the covariance matrix (2x2)

$$V_p = \sum_{i=1}^{n} (p_i - v_p)(p_i - v_p)^t / (n - 1)$$

3. Multiplying the matrix V_p by (n-1) we obtain the matrix

$$S_p = (n - 1) V_p$$

4. The eigenvalues λ_1 and λ_2 of S_p are calculated; the possibilities will be:

- $\lambda_1 = 0$ or $\lambda_2 = 0$ then the sample P is degenerate, S is not invertible and there are three constants a, b and c such that $ax + by + c = 0$. In this case the points of the sample lie on a straight line.
- $\lambda_1 = \lambda_2 > 0$ then the points of the sample assume a circular form.
- $\lambda_1 > \lambda_2 > 0$ then the points assume an elliptical form.

The eigenvalues, solutions of the characteristic equation of normalized symmetrical dispersion matrix

$$A = S_p / t_r(S_p)$$

assume the form:

$$\lambda_1 = [1 + (1 - 4 * \mathrm{Det}(A))^{1/2}]/2$$

$$\lambda_2 = [1 - (1 - 4 * \mathrm{Det}(A))^{1/2}]/2$$

Putting $Dx = (1 - 4 * \mathrm{Det}(A))^{1/2}$ one has

$$\lambda_1 = [1 + Dx]/2$$

$$\lambda_2 = [1 - Dx]/2$$

with λ_1, λ_2 which have the following properties:

$$\lambda_1 + \lambda_2 = 1 \quad ; \quad \lambda_1 - \lambda_2 = Dx$$

Therefore taking Dx as index for definition of the course described by the points one has:

$Dx = 1$	the course of the points is a straight line;
$Dx = 0$	the points are on a circle;
$0 < Dx < 1$	the points are on an ellipse.

4.3 Algorithm for compressing data in R3

The need for thinning in a photogrammetric restitution that can be used to construct a three dimensional model led us to extend the algorith described above to the three dimensional case. This is because the redundancy of points may occur both in the "planimetric" tracing and in the "altimetric" variations produced by projections and recesses from the general plane of projections of the front surface.

Considering a sample $P = (p_1, p_2, \dots, p_n,)$ of points $p_i = (x_i, y_i, z_i)$ defined in R3, the mean of the sample is

$$v_p = \sum_{i=1}^{n} p_i / n$$

and the third order matrix is

$$Vp = \sum_{i=1}^{i} (p_i - v_p)(p_i - v_p)^t / (n - 1)$$

A is used to indicate the normalized matrix

$$A = (n - 1) V_p / tr (V_p) \qquad [1]$$

which therefore has a unitary trace Tr(A)=1.
The characteristic equation of A will be given by

$$| A - \lambda I | = 0$$

and therefore, calculating this determinant we obtain:

$$- \lambda^3 + tr(A)\ \lambda^2 - M_2(A)\lambda + Det(A) = 0 \qquad [2]$$

where $M_2(A)$ is the sum of the determinants of the principal minors of second order of matrix A.
Special attention must be given to the determinant of A; as long as the points in the sample are coplanar, the determinant of the matrix A is always nil; therefore the characteristic equation of A becomes

$$- \lambda\ [\ \lambda^2 - \lambda + M_2(A)\ ] = 0$$

It follows that one eigenvalue of A will therefore always be nil, $\lambda_3 = 0$, and the other two eigenvalues λ_1, λ_2 are calculated using the equation

$$\lambda^2 - \lambda + M_2(A) = 0$$

These eigenvalues give the information of the form assumed by P in 3D space in a way similar to what we have already seen for the 2D case. The general structure of the algorithm can thus unfold:

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1. having set the tolerance required for
   allignment;
2. take the first three points from P;
3. memorize the first point;
4. repeat until all the points from P
   have been taken;
   4.1. calculate the matrix A and its
        eigenvalues;
   4.2. if Dx is greater than the
        tolerance imposed then take
        another point from P;
   4.3  if the number of points taken is
        greater than Nmax remove the
        first point currently taken
        otherwise memorize the pen-
        ultimate point taken, the point
        memorized becomes the first point
        taken;
5. take the third point from P;
6. memorize the last point taken.
```

The efficiency of the algorithm in terms of thinning and geometrical faithfulness of the compacted sample is governed by the values chosen for Dx and Nmax.
Choosing appropriately the value for Dx (generally between 0.9 and 1) one can programme a greater or lesser degree of thinning according to the requirements to be satisfied or the results wanted. The interesting aspect of this algorithm is that it permits elimination of background noise and, in the architectural example being considered, memorization of only the angles essential for overall geometrical description, which serves for definition of a calculation model for structural analysis.
The decision to introduce a value Nmax of points used for calculation of the matrix A derives from the need to eliminate errors in identification of the point of intersection between two consecutive straight lines, restricting the field of search to limited sections. In fact, if the sample has a high point density, introduction of a new point not alligned with the previous ones into the calculation of Dx does not significantly influence the value. One must therefore find a compromise between elimination of noise and respect for the geometry of the object. Tests performed suggest that an appropriate maximum number of points is between 5 and 15; the closer the points, the lower Nmax should be. Figure 3 shows how this algorithm operates on the points that describe the perimeter of a quoin, acquired with the 3D numerical restitution described.

5. CONCLUSIONS

The restitution test and subsequent treatment of the data show how standardization of procedures ought not to be delayed if data files are to be created and stored that can really be used in different types of numerical processing. In the case of the Colosseo this work can help to develop specifications and methodologies that can be extended to restitution of the entire face. The data thinning and treatment performed has made it possible to develop a procedure for identification of those vertexes which geometrically can well approximate the geometry for the purposes of inclusion in finite element calculations (Figures 4-5). Similarly, the topological and qualitative coding used are indispensible preliminaries to subsequent creation of specific topic maps and realistic computer graphics displays.
On the other hand it should be remembered that restitution performed with the methods described here requires a great deal of work by the operator, much more than traditional restitution.

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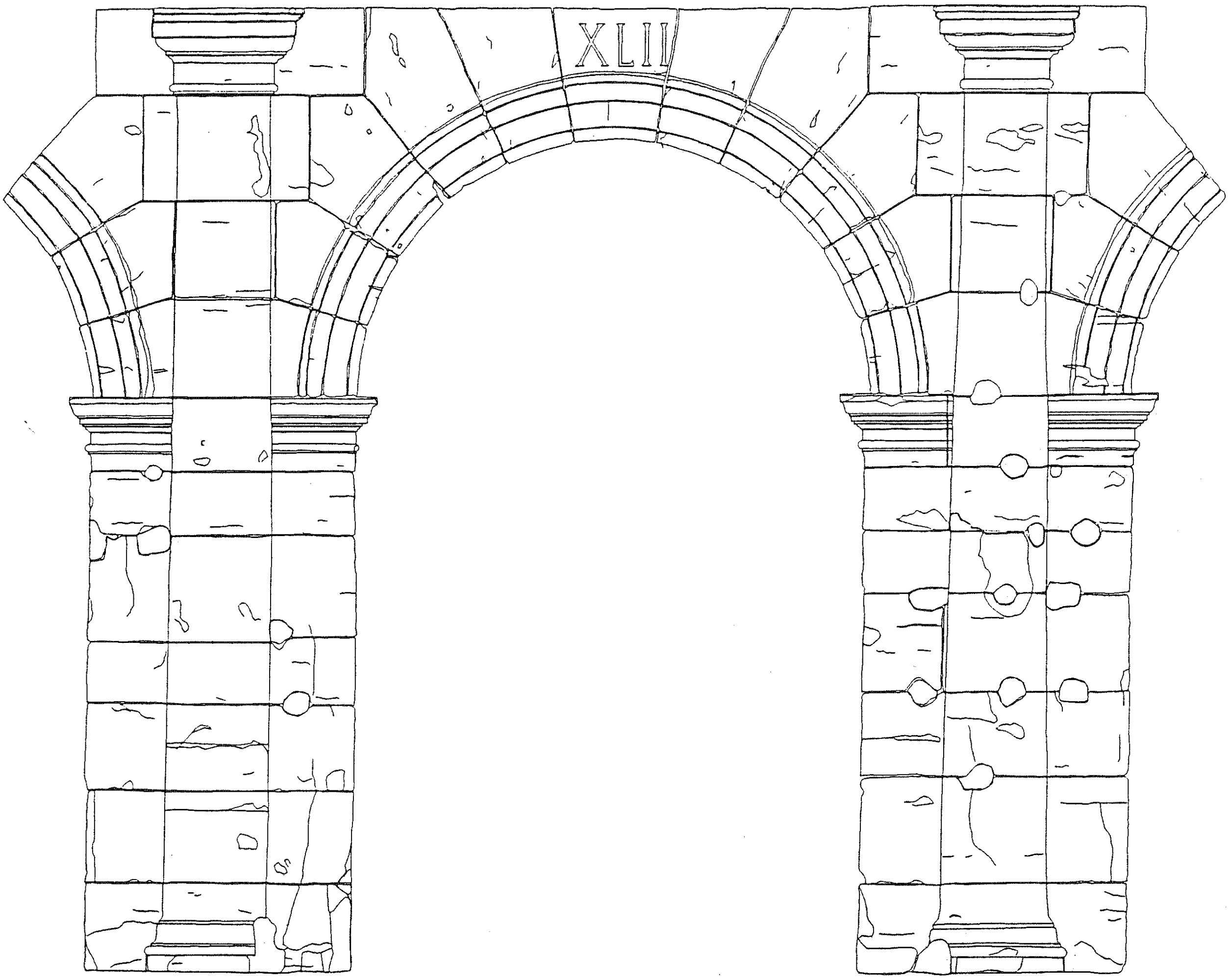


FIGURE 1

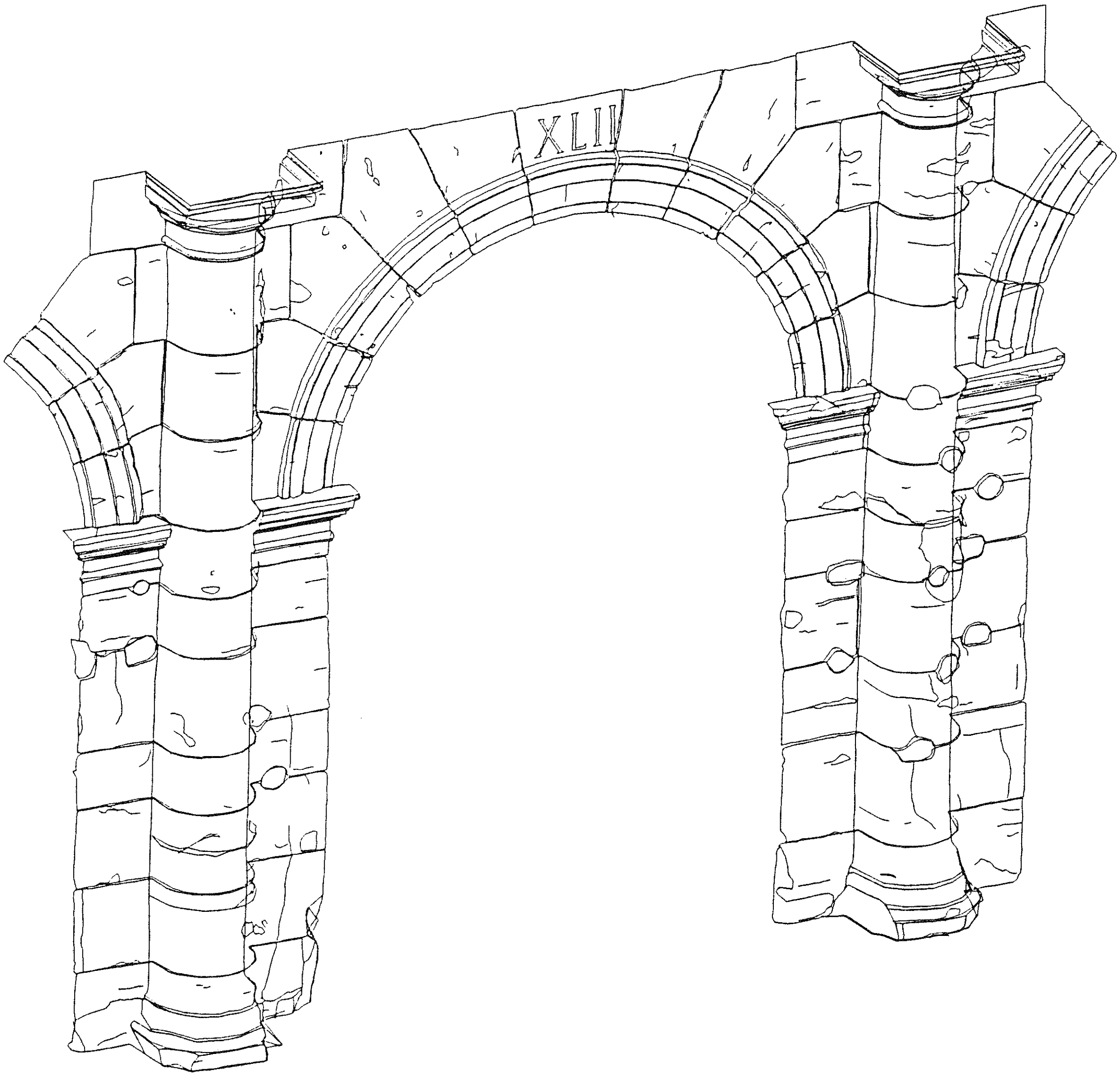


FIGURE 2

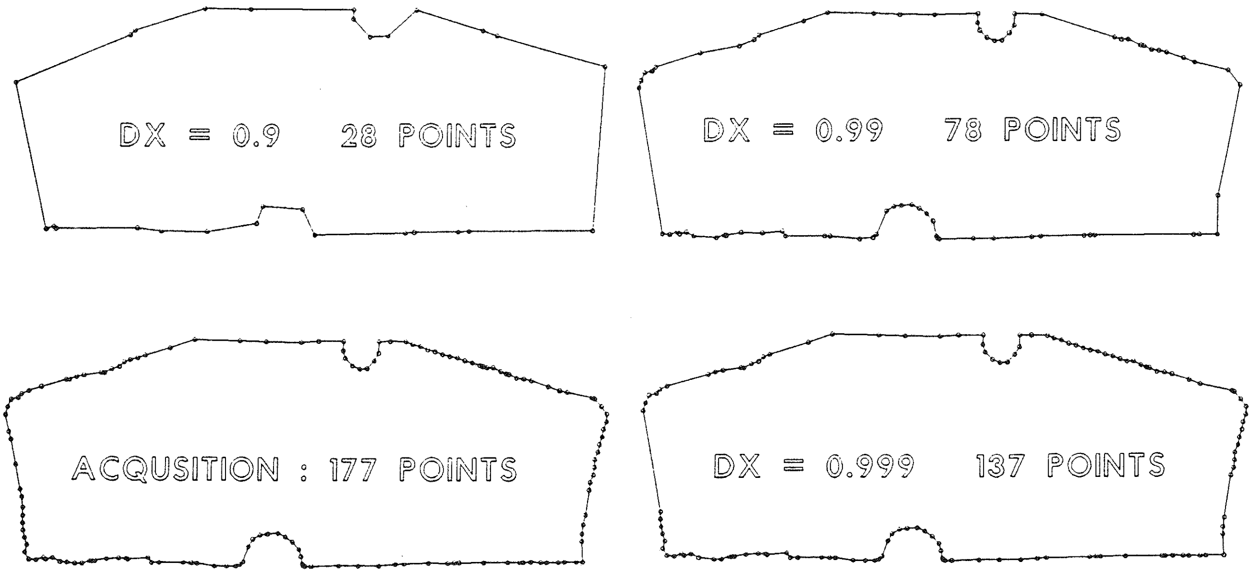
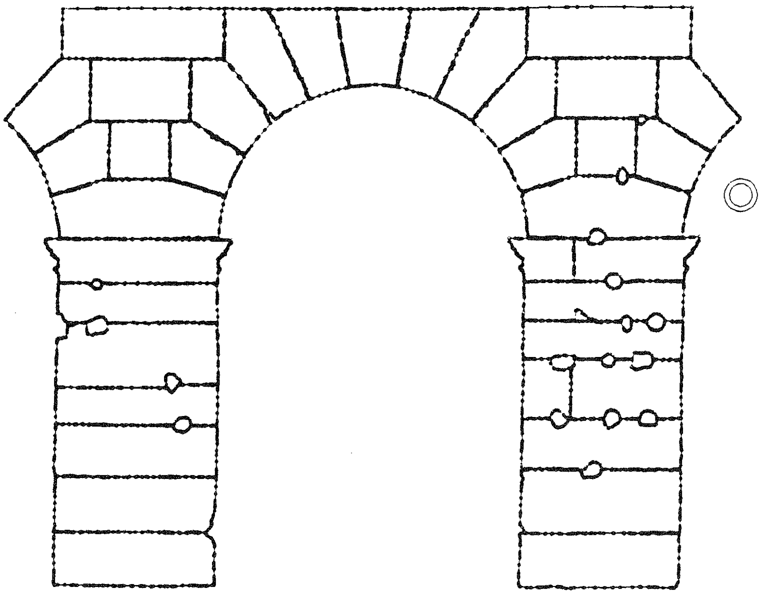
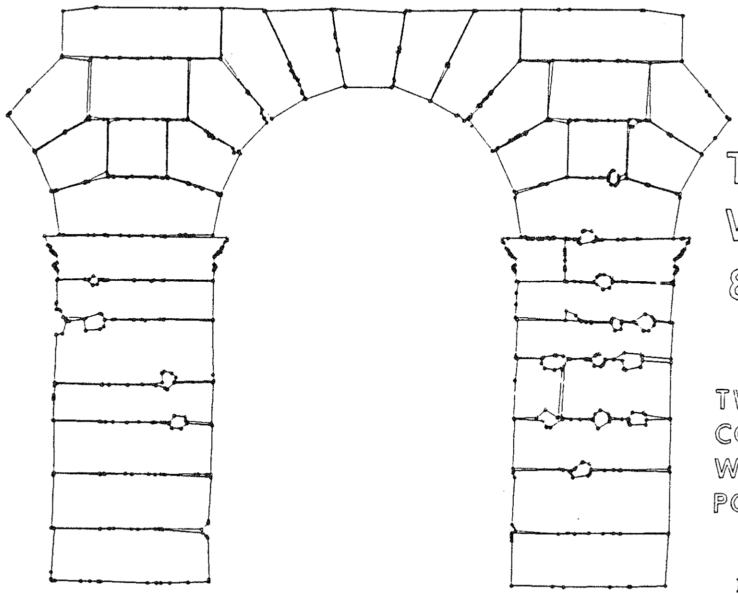


FIGURE 3



ORIGINAL PLOTTING:
3680 POINTS

FIGURE 4



THINNED PLOTTING
WITH DX = 0.095
857 POINTS

TWENTY SECONDS FOR THIS DATA
COMPRESSION WITH ALGORITHM
WRITTEN AND COMPILED IN BASIC:
PC IBM 386 33 Mhz DOS V. 5.0

FIGURA 5