AN APPLICATION STUDY FOR MAPPING CRACKS IN BUILDINGS

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1. INTRODUCTION

The appearance and development of cracks in buildings and
other engineering constructions is familiar to civil engineers.
When cracks appear in a building, the residents in it begin to
worry about the safety aspect and so, a civil engineer will be
called upon to investigate the structural stability. If the
building is large and there are cracks in different parts, a
visual inspection by the engineer will not suffice. A thought-
ful engineer would then logically request for the maps of all
cracks .In some cases,he may also request for the monitoring of
the cracks for possible enlargements and extensions. This
points to the need for establishing a working procedure for
the mapping of cracks and also for periodic mapping of cracks.

Although various other methods and procedures are available for
use, the development and consistent use of close-range
photogrammetric method has obvious advantages. The capability
of the method in producing acceptable and comparable results
during periodic evaluations and where necessary,the repeatabi-
lity of map compilation procedures, are just two of the main
advantages.In order to render the method more widely acceptable
the use of non-metric cameras and computer supported
digitising equipment merit serious considerations. Further,
as the investigations reported here were directed mainly
to the needs of advanced students in a bachelors degree
program in civil engineering, as per circumstances, necessary
simplifications were made. Three different types of non-metric
cameras were used. These are the large format Bronica camera,
the half frame 35mm Nimslo stereo camera and a representative
popular 35mm Yaschica brand camera. For measurement of
photo-coordinates the Wild Aviolyt BC2 and a Calcomp 9000
series digitizer were used. The photo-coordinate data were
procured by using either the original negatives or commerci-
ally obtained enlarged paper prints. The investigation attem-
pts to determine the feasibility of using simple commercial
equipment for mapping of cracks in buildings.

2. THE PORTABLE CONTROL POINTS FRAME

Figure 1 shows the left hand photograph of a stereopair
depicting the crack with the 3-dimensional control points
frame positioned in front of it. The frame was designed in
three layers of rectangular loops of steel, with the second
loop smaller than the first and the third loop smaller than the
second. Now,the control points are marked in paint on the frame
and thus these are situated in three different planes. The
crack appears in the middle part of the photograph.

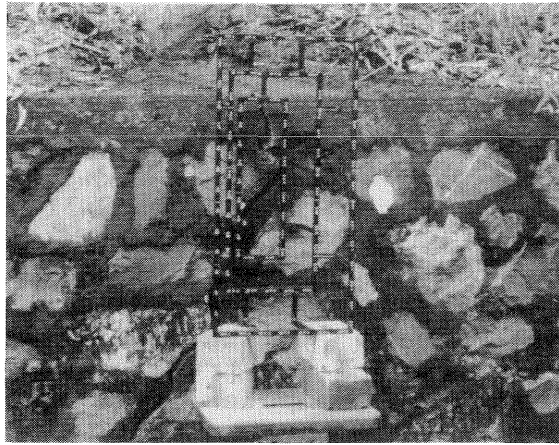The largest dimension of the frame is nearly 67 cm long. The

Fig. 1:Photograph of crack

scale of the photograph is 1:30. Adopting a 50 μm size
for the image of the control point target, its corresponding
dimensions on the iron frame should correspond to 30x50 =1.5mm.
Each control point was point marked as a white cross with each
of the cross lines 1.5mm thick marked in white against a 5mm
diameter circular red mark for the background. The control
points were approximately equi-spaced and the completed frame
contained nearly 100 such points. The finished frame was
considered stable and yet portable.

The next task is the measurement of the three dimensional co-
ordinates of the control points. It is usual for someone to
consider a traditional survey method involving triangulation
and trilateration for completing such a task. Such methods have
obvious limitations, particularly in view of the small size of
the object and the special design of the frame. Hence, possibi-
lity of using a non-traditional survey method was explored. The
three dimensional coordinate measuring machine, normally used
in a mechanical metrology laboratory, was spotted and as it
suited the purpose it was favourably considered and selected
for use.

The XYZAX M600A coordinate measuring machine operates in a
combination of electronic and mechanical modes. The measuring
range extends upto 600mm in x,400mm in y and 300mm in z. The
specifications for repeatability is indicated by σ= 1.5 μm.
The instrument is easy to use and an electronic paper tape
printer prints out the coordinates of a measured point. As a
standard procedure 3 repeat measurements of each control point
were made.

The longest linear dimension of the control points frame was
670mm and so all points could not be measured with a single
measurement set up. Measurement was done in two overlapping
sections so as to cover the entire frame. The common control
points situated in the overlapping part of the frame were mea-
sured in both the sections. These redundant measurements were
used for a 3-dimensional coordinate transformation of data into
a common system. The equations and the least squares procedure

for coordinate transformation are described in detail in wolf (1974). These equations are:

$$X = s(m_{11}x + m_{21}y + m_{31}z) + T_x$$
$$Y = s(m_{12}x + m_{22}y + m_{32}z) + T_y$$
$$Z = s(m_{13}x + m_{23}y + m_{33}z) + T_z \qquad ...(1)$$

Where, (X,Y,Z) refer to the 3-dimensional coordinates of a control point measured in the overlapping part in the first set up and (x,y,z) refers to the 3-dimensional coordinates of the same point measured in the second set up. The equations provide for 7 parameters - 3 for translations, 3 for rotations and 1 for scale change. A computer proagram was written and implemented on a prime 750 computer and used in data processing. It is to be noted here that the x and y axes of the 3-dimensional coordinate system are nearly contained in the plane of the front face of the frame and at the time of photographing, an attempt was made to render this plane parallel to the face of the wall containing the crack.

3. DETERMINATION OF THE POSITION OF POINTS ON THE CRACK LINE

Karara (1985) has reviewed the methods and procedures used in photogrammetric 3-dimensional mensuration, particularly when the data source is a non-metric camera. Of the four major methods discussed there, the Direct Linear Transformation(DLT) method was selected primarily because of the readily available computer program code. However, the latest software based on DLT was out of reach for various reasons.

The mathematical and conputational treatment of the DLT method is well described in Marzan & Karara(1975). The following basic collinearity equations are used in least squares computations.

$$x + \Delta x = \frac{L_1X + L_2Y + L_3Z + L_4}{L_9X + L_{10}Y + L_{11}Z + 1}$$

$$y + \Delta y = \frac{L_5X + L_6Y + L_7Z + L_8}{L_9X + L_{10}Y + L_{11}Z + 1} \qquad ...(2)$$

Where,
  x,y :   refer to comparator photo coordinates of a given point in left/right photograph,
  $\Delta x, \Delta y$: image distortions which are calculated using parameters obtained in the DLT solution,
X,Y,Z :   the object space coordinates of the considered point&
$L_1...L_{11}$: the DLT parameters.

The computational scheme provides various options in respect of the image distortions in the form of parameters K_1, K_2, K_3, P_1 and P_2. When the full option is selected, the effect of linear, symmetric and asymetric lens distortions are compensated.

The main computations are carried out sequentially. In the first step, the applicable DLT parameters of each of the

photographs are calculated. This could be considered as the calibration mode. Now, the DLT parameters of at least two over-lapping photographs and the photo-coordinates of a given point in each of the photographs is next used in the second step for the computation of the 3-dimensional object space coordinates of the selected point situated on the crack line. A computer program for the second step computations was developed and implemented on the prime 750 computer system.

As the front face of the wall is rendered parallel to the x y plane of the frame, we could just extract the x and y co-ordinates from the computed 3-dimensional coordinates of the various selected points on the crackline and use it to plot the map. In order to make the plotting appear smooth, it is necess-ary to interpolate the position of a number of intermediate points. A procedure for this is discussed in the next section.

4. CUBIC SPLINE INTERPOLATION

The use of a digital computer to generate curves that pass through a given set of points adds a new dimension to drawing techniques. When the equation to a curve is not known, an interpolation scheme could be used. This involves specifying the boundary conditions for the selected curve in order to determine the coefficients for a given polynominal curve form. Cubic splines or Bezier curves or B-spline curves are popularly used in engineering.Because of its simplicity,the natural cubic spline was selected for use.
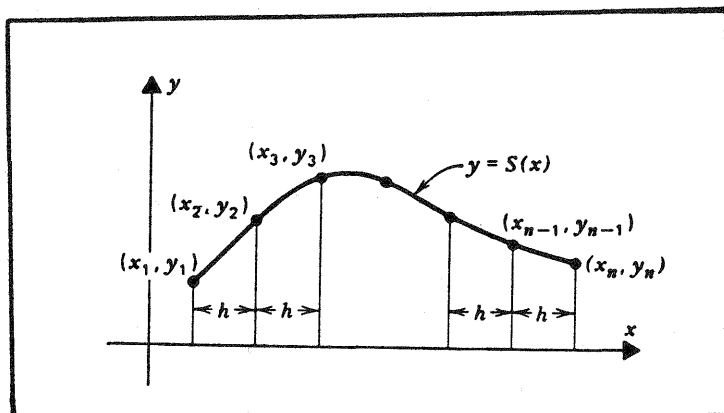

Fig. 2: Cubic spline interpolation

A brief description of the natural cubic spline only is given here. A very clear description of the cubic spline curves may be found in Rorres and Anton (1986). Suppose we are given n points in the xy plane $(x_1,y_1),(x_2,y_2),\ldots,(x_n,y_n)$
and that we wish to find an interpolating curve passing through all these points(see fig.2). For convenience,we take the points to be equally spaced in the x-direction and let $x_{i+1}-x_i = h$, $i=1,2,\ldots,n-1$. The desired cubic spline is given by,

$$S(x) = \begin{cases} a_1(x-x_1)^3 + b_1(x-x_1)^2 + c_1(x-x_1) + d_1 \\ \qquad\qquad\qquad\qquad\qquad\qquad x_1 \leqslant x \leqslant x_2 \\ a_2(x-x_2)^3 + b_2(x-x_2)^2 + c_2(x-x_2) + d_2 \\ \qquad\qquad\qquad\qquad\qquad\qquad x_2 \leqslant x \leqslant x_3 \\ \quad . \qquad\qquad . \qquad\qquad\qquad . \\ \quad . \qquad\qquad . \qquad\qquad\qquad . \\ \quad . \qquad\qquad . \qquad\qquad\qquad . \\ a_{n-1}(x-x_{n-1})^3 + b_{n-1}(x-x_{n-1})^2 \\ \quad + c_{n-1}(x-x_{n-1}) + d_{n-1}, \qquad\qquad x_{n-1} \leqslant x \leqslant x_n \end{cases} \quad \dots(3)$$

The coefficients could be expressed using the following expressions.

$$a_i = (M_{i+1} - M_i)/6h$$

$$b_i = M_i/2,$$

$$c_i = (y_{i+1} - y_i)/h - (M_{i+1} + 2M_i)h/6$$

$$d_i = y_i \qquad\qquad\qquad \dots(4)$$

for $i=1,2,\dots,n-1$, where $M_i = S''(x_i)$, $i=1,2,\dots,n$.

The natural cubic spline is obtained by using the two simplest mathematical conditions $M_1 = M_n = 0$. The other quantities $M_2,\dots M_n-1$ are then determined by solving the following $(n-2) \times (n-2)$ linear system.

$$\begin{bmatrix} 4 & 1 & 0 & 0 & \dots & 0 & 0 & 0 \\ 1 & 4 & 1 & 0 & \dots & 0 & 0 & 0 \\ 0 & 1 & 4 & 1 & \dots & 0 & 0 & 0 \\ . & . & . & . & & & & \\ . & & . & & & . & & \\ . & . & . & . & & & & \\ 0 & 0 & 0 & 0 & \dots & 1 & 4 & 1 \\ 0 & 0 & 0 & 0 & \dots & 0 & 1 & 4 \end{bmatrix} \begin{bmatrix} M_2 \\ M_3 \\ M_4 \\ . \\ . \\ . \\ M_{n-2} \\ M_{n-1} \end{bmatrix} = \frac{6}{h^2} \begin{bmatrix} y_1 - 2y_2 + y_3 \\ y_2 - 2y_3 + y_4 \\ y_3 - 2y_4 + y_5 \\ . \\ . \\ . \\ y_{n-3} - 2y_{n-2} + y_{n-1} \\ y_{n-2} - 2y_{n-1} + y_n \end{bmatrix} \quad \dots(5)$$

The values of M_i, $i=1$ to n substituted in eq (4) will yield numerical values for the coefficients a_i, b_i, c_i and d_i, with $i = 1,2, \dots, n$.

Once the polynomials are defined, by specifying a suitable interpolation interval Δx, the array of (x,y) coordinates of a large number of points situated on the spline curve are calculated. On a computer driven plotting table the actual curve is plotted using these values.

5. INVESTIGATIONS

As indicated already, the control points marked on the iron frame were measured on the coordinate measuring machine in two overlapping sections. A 3-dimensional coordinate transformation

program was used to screen the data, eliminate mistakes using a 3 σ-criteria, and transform the measurements to a common system and estimate the accuracy of the resulting control points data.

A typical crack line was selected and photographs were obtained using three types of cameras as indicated in the introduction section. Paper print enlargements of 25 x 30 cm were obtained commercially for working with the digitizer used as a comparator. In order to compare results, some measurements using negatives were also carried out on the Wild Aviolyt BC2. The Direct Linear Transformation program (DLT) was used to compute the basic X,Y,Z, coordinate data of control and detail points. Also,an attempt was made to determine the accuracy of the computed detail points. The investigations included the scheme to determine the necessary minimum number of control points in data reduction. To a limited extent, the minimum number of DLT parameters required to be carried in the solution was also investigated. A computer program for cubic spline interpolation and another computer program for plotting the results were also developed as part of the investigations. A summary of the Saliant results obtained is given in the next section.

6. SOME RESULTS

Measurements on the control points frame:
Number of repetitions used for each point = 3
Number of control points for which the 3 dimensional coordinates were determined = 90
Mean standard errors: 0.12mm in x, 0.12mm in y, 0.21mm in z, 0.27mm in position.
Computations using the DLT program:

In stating the results of computations using the DLT program, the term POS is used for representing the computed positional accuracy of an object space point. It is computed as the square root of the avg. of the variances of the computed X,Y and Z coordinates which are extracted from the inverse of the normal matrix. Photocoordinates were measured on 4 overlapping photographs, each taken using the Bronica, Yashica and Nimslo cameras. Only in case of Bronica photographs, measurements were made both on the Wild Aviolyt BC2 and the CalComp 9000 digitizer. In the other two cases, viz., Yashica and Nimslo, only the Calcomp 9000 digitizer was used with 25x30cm enlarged paper prints. The results of data processing are grouped as necessary for the various comparisons.

(a) Wild Aviolyt BC2 Vs Calcomp 9000 digitizer: Camera:Bronica; value of POS (i) using Wild Aviolyt BC2 : 0.13mm (ii) using Calcomp 9000 digitizer: 0.76mm

(b) Variations in results due to the number of parameters (IP) used in the DLT solution:

Table 1: Accuracy expressed as POS (in mm) due to variation in IP

Camera	Comparator	POS IP=11	POS IP=12	POS IP=14	Remarks
Bronica	Wild BC2	0.13	0.11	0.12	No.of pho-
Bronica	Calcomp.9000	0.76	0.61	0.62	tos used
Yashica	Calcomp.9000	0.74	0.69	0.66	in each
					case = 2

(c) Variations in results due to different type of camera:

Table 2: Accuracy expressed as POS (in mm) due to variation of camera type

Camera	No.of photos	POS	Remarks
Bronica	2	0.76	The Calcomp
Yashica	2	0.74	9000 digitizer
Yashica	2	0.89	was used in all
Nimslo	2	1.72	cases
Nimslo	2	1.99	
Nimslo	4	1.02	

(d) Variations in results due to differences in number of control points (N) used :
Type of camera : Bronica
Type of comparator : Calcomp 9000 ; POS in mm.
N = 90, POS = 0.76 ; N=80, POS = 0.74 ; N=70, POS= 0.74,
N = 60, POS = 0.75 ; N=50, POS = 0.77 ; N=40, POS= 0.76.

The results obtained could be treated as fairly representative. The combination of the camera type, comparator type and number of photographs that could be used in crack mapping could be selected based on the accuracy specifications for the job on hand. For example Yashica camera, Calcomp 9000 digitizer and two photographs could be used if a 1mm standard error is considered sufficient for the crack mapping job.

7. CONCLUSIONS AND RECOMMENDATIONS

Only limited data analysis is reported in this paper. Hence, the conclusions drawn here should be used with caution.

(a) The comparison of obtainable accuracy using the camera types Bronica, Yashica and Nimslo indicates that use of Bronica camera yields the most accurate results. However,considering the cost factor, the selection and use of a Yashica camera would be quite reasonable .The Nimslo camera, though it takes four overlapping photographs per exposure, did not seem to offer any advantage.

(b) Best results were obtained when Wild Aviolyt BC 2 was used for measurement of photo-coordinates. However,in applications where a standard error in position of 1mm would be acceptable, the use of Calcomp 9000 digitizer is adequate.

(c) The optimum number of control points that could be used in crack mapping was not established conclusively. From practical considerations and with due regard to partial results obtained the use of a minimum of 40 control points is suggested.

(d) As there does not appear to be any significant gain by using larger number of DLT parameters, it is suggested that only 11 parameters be used in the solution.

(e) The calibration frame was considered structurally stable and yet easily portable in a car boot. In a country like Singapore, situated close to the equator, the temperature variation during the year is quite small -say from 26 to 32 C. Hence, the linear expansions in the frame were considered negligible. Also, the coordinate measuring machine used for 3-dimensional measurement of the relative position of control points was found to be quite acceptable for the job.

(f) For a suggested accuracy specification of 1mm in the position of a located point on a crack line, a combination of Yashica camera, enlargement of paper prints to 25x30 cm size, use of Calcomp 9000 digitizer, and use of 11 parameter DLT solution based on a 40 control points data may be considered adequate.

(g) An extended study to consider the problems of mapping cracks of linear dimensions greater than 1 meter length is recommended.

8. ACKNOWLEDGEMENTS

9. REFERENCES

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