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Examples of the Use of Photogrammetry In Forensic Engineering and Accident Reconstruction

by Joel T. Hicks, P.E. (049F)

Introduction

One definition of Photogrammetry is, "The use of photographs for making maps."[1] For our purposes, photogrammetry means the extraction of dimensions in one plane from oblique view photographs. Although there is software to analyze in three dimensions, this discussion is limited to a single surface or plane. The software chosen for illustration is TRANS4 by J. Rolly Kenny[2], which employs the Four-Point Transformation Method.

To start an analysis a print is attached to a digitizer pad. Then, with the software primed and waiting on a signal, a mouse button is clicked when the cross-hairs of the mouse are placed over a point on the print. The digitizer will send a stream of data back to the computer, and the software will read and store the location of the pad under the print at the point.

When all points of interest have been located in pad coordinates, the real or measured coordinates of four of the points are entered by hand. The software then computes the real coordinates for all of the points. The four points of reference are called Base Points (BP). No three of them can be in a line, and all points of interest must lie on the same plane.

Theory

All software manuals should discuss the theory of the techniques used. Two pages of the TRANS4 manual are included here as Appendix A. Note on the second page that two NAFE members are listed as references, and the author has written a more extensive discussion of the theory in an SAE paper.

Case Examples

Instead of going through the theory in detail, the purpose of this paper is to help you to understand how photogrammetry can help you do your work better. Learning how to use this tool could cause you to change the ways you collect scene evidence. Of particular concern is the time you have to spend within a traffic way. Three examples are presented.

Joel T. Hicks, P.O. Box 190822, Little Rock, AR 72219-0822

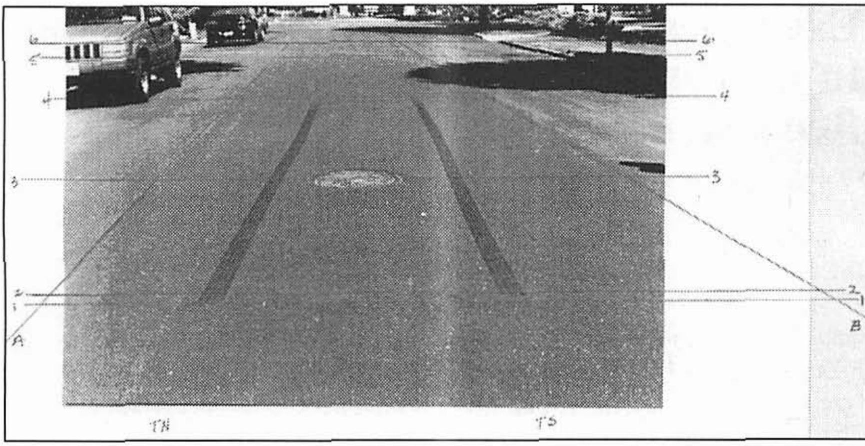

Figure 1

1. The first case concerns a car striking a child on a skateboard that went into the street from the driveway of # 77, as shown in Figure 2. The assignment was to a) determine the distance of the tire marks, and b) to relate that to speed of the car prior to maneuvers.

The photo used in the photogrammetry, Figure 1, was actually an enlarged color copy of one taken toward the east soon after the incident. The scene was surveyed much after the incident, but key features seen in the photo still could be seen and located later. Those features have been drawn to scale in Figure 2, and

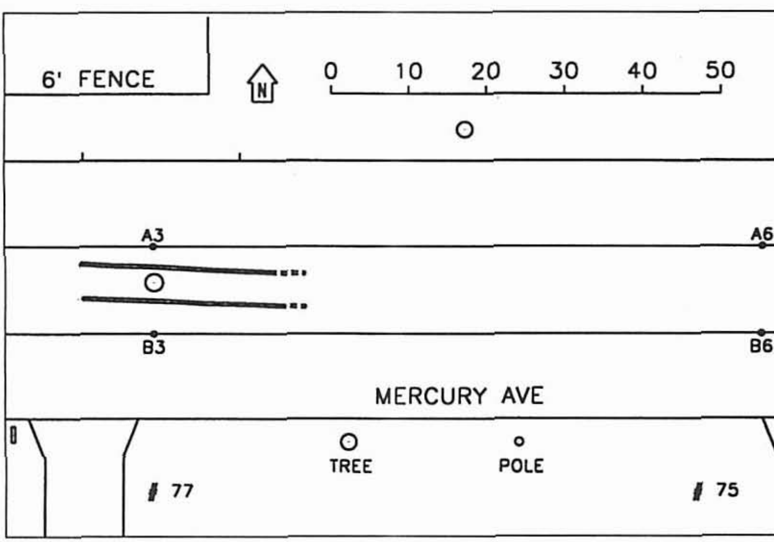

Figure 2

include the manhole cover, the width of the pavement construction joint lines, and the relative distance from the manhole to the driveway of # 75 and the pole.

The pavement construction joint lines were 11.7 feet apart north-to- south. The distance from the manhole cover to the west edge of the driveway for # 75 was 78 feet. As shown in Figure 3, the computed total distance of the tire marks

TRANS4 Source File: G98184A(Printed from Editor) **Page: 1**
Date6/20/98 By JTHCase HP3306 Roll CM Frame 4 Run A Plot P 0.50L
Comments:Photo Units inches +/- 0.010 Real Units feet
New York Central Mutual tire marks to the east, centered on man hole cover.

C1=-1.5788480E+01 C2=-1.1580390E-02 C3= 3.3641060E+00 C4=-1.5343930E-03
C5=-1.4396630E-01 C6= 1.0066990E+01 C7=-6.3916180E-01 C8=-1.0793030E+00

Pt.		MEAS.	- PHOTO	MEAS.	- REAL	COMPUTED	REAL	COORDINATES	
No.	NAME	Xp	Yp	Xr	Yr	Xc	Yc	Dx	Dy
1	A1	0.53	3.19	0.00	0.00	-9.4	11.6	0.0	0.0
2	A2	0.63	3.30	0.00	0.00	-9.0	11.6	0.0	0.0
BP	A3	1.97	4.70	0.00	11.66	0.0	11.7	0.1	0.0
4	A4	2.93	5.70	0.00	0.00	19.2	11.7	0.4	0.0
5	A5	3.43	6.22	47.00	11.66	51.3	11.7	1.1	0.1
BP	A6	3.61	6.40	78.00	11.66	78.0	11.7	2.0	0.1
7	B1	10.32	3.22	0.00	0.00	-9.7	-0.0	0.0	0.0
8	B2	10.12	3.34	0.00	0.00	-9.3	-0.0	0.0	0.0
BP	B3	7.78	4.72	0.00	0.00	0.0	-0.0	0.1	0.0
10	B4	6.14	5.70	0.00	0.00	19.5	-0.1	0.4	0.1
11	B5	5.25	6.22	47.00	0.00	52.6	-0.0	1.1	0.1
BP	B6	4.96	6.39	78.00	0.00	78.0	-0.0	2.0	0.2
13	MHN	3.92	4.71	0.00	0.00	0.0	7.8	0.1	0.0
14	MHC	4.46	4.71	0.00	0.00	0.0	6.8	0.1	0.0
15	MHS	5.01	4.71	0.00	0.00	-0.0	5.7	0.1	0.0
16	MHE	4.49	4.82	0.00	0.00	1.3	6.7	0.1	0.0
17	MHW	4.48	4.60	0.00	0.00	-1.1	6.8	0.1	0.0
18	TN1	2.60	3.20	0.00	0.00	-9.4	9.2	0.0	0.0
19	TN2	2.66	3.31	0.00	0.00	-9.0	9.2	0.0	0.0
20	TN3	3.44	4.71	0.00	0.00	0.1	8.8	0.1	0.0
21	TN4A	3.90	5.56	0.00	0.00	14.8	8.1	0.3	0.0
22	TN4	3.96	5.70	0.00	0.00	19.3	8.0	0.4	0.0
23	TS1	6.41	3.22	0.00	0.00	-9.6	4.7	0.0	0.0
24	TS2	6.35	3.34	0.00	0.00	-9.1	4.7	0.0	0.0
25	TS3	5.67	4.71	0.00	0.00	-0.0	4.3	0.1	0.0
26	TS4A	5.21	5.60	0.00	0.00	16.1	3.7	0.3	0.0
27	TS4	5.16	5.70	0.00	0.00	19.4	3.6	0.4	0.0
28	TN	2.60	3.21	0.00	0.00	-9.4	9.3	0.0	0.0
29		2.96	3.86	0.00	0.00	-6.5	9.1	0.1	0.0
30		3.37	4.61	0.00	0.00	-1.0	8.9	0.1	0.0
31		3.57	4.95	0.00	0.00	2.9	8.7	0.1	0.0
32		3.70	5.17	0.00	0.00	6.2	8.5	0.2	0.0
33		3.81	5.40	0.00	0.00	10.8	8.3	0.2	0.0
34		3.91	5.61	0.00	0.00	16.3	8.1	0.3	0.0
35	TS	6.35	3.34	0.00	0.00	-9.1	4.7	0.0	0.0
36		5.87	4.28	0.00	0.00	-3.9	4.5	0.1	0.0
37		5.61	4.82	0.00	0.00	1.2	4.3	0.1	0.0
38		5.52	5.01	0.00	0.00	3.7	4.2	0.1	0.0
39		5.44	5.19	0.00	0.00	6.6	4.0	0.2	0.0
40		5.31	5.43	0.00	0.00	11.5	3.9	0.2	0.0
41		5.19	5.63	0.00	0.00	17.0	3.7	0.3	0.0

Figure 3

was about 29 feet, the eastern 4 feet of which were lighter than the rest. These distances are shown as coordinates in the computed data of Figure 3, rather than directly as distances.

Figure 3 is a report of the photogrammetry study, and lists on the top line G98184A as the Source File. The points listed down the left "NAME" column correspond to the photograph markings. "A1" corresponds to the intersection of the north joint line (A) and the west end of the right tire mark (1). "MH" refers to the manhole cover, and "TN" refers to the north (vehicle right) tire mark.

The "MEAS.-PHOTO" columns are the x and y coordinates of the digitizer pad under the points. The "MEAS.-REAL" columns are the real measurements as determined by the scene survey. Only six points, including B3 as origin, were established from the scene survey. Four of these six are shown as Base Points (BP in the left column), which were selected for computation of all other points. The pole location (#5) could not be determined accurately in the shadows of the photograph.

The computed coordinates from the B3 origin are shown in the first two columns under the heading COMPUTED REAL COORDINATES. X is the distance east(+) or west(-) of B3, and Y is the distance north(+) or south(-) of B3.

The columns Dx and Dy indicate the relative accuracy of the calculated values. For example, the point A6 carries with it a potential error of 2 feet e-w (because of its distance from the camera,) while its potential error n-s is 0.1 ft. Both potential errors correspond approximately to the width of a line on the photograph.

Figure 4

2. The second case involves a motorcycle traversing a roadway repair area that was left with an unexpected bump. The bump caused a bike and rider to spill. At issue was the sharpness of the change in elevation.

The motorcycle in Figure 4, a companion to the subject machine, was identified by a Harley-Davidson dealer as a Softail Custom having an MH90-21 tire. The front rim outside diameter was 22 inches. Striations in the pavement can be followed to the right as the elevation rises in several plateaus. Assuming that the camera was normal to both the wheel plane and the striations, the height of the original pavement would be about 3 to 4 inches above the dip where the tire rests, and the rise at the front of the tire would be about 2 inches. This estimate is by simple scale proportional ratios, or hand photogrammetry.

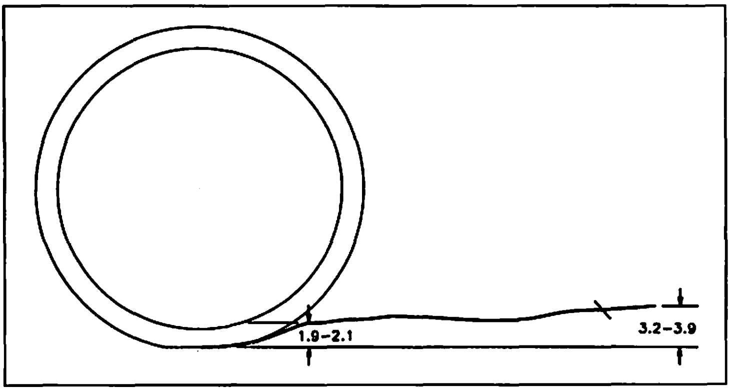

Figure 5

Figure 5 is the profile of the pavement shown on a drawing, and Figure 6 is the TRANS4 data page. In this case there were two data pages, one for the pavement stripes establishing the horizontal reference, and another where the camera was considered to be level. The difference amounts to rotation of the drawing slightly. Regardless of the reference, the first step rose about 2 inches in 8 inches of travel.

As shown in Figure 6, TRANS4 predicted the same elevation change as the simple estimate, but the camera no longer has to be perpendicular to the plane being studied. The wheel and striations have to lie in the same plane, but the plane does not have to be vertical and it does not have to be perpendicular or parallel to the camera or anything else.

In order to determine the rise and run for all of the points, the profile x's and y's can be compared to those of point R5, at the base of the tire. The origin is at the rim center, so the elevation of point R5 is negative. The other points along the PROFIL are less negative than R5, and may be converted to positive elevations by adding 12.7 to all of the y values of interest. It may be noticed that the profile was digitized from right to left, and that point 29 is near the referenced 2 inch rise in 8 inches of travel.

An alternate to all of this calculation would be to transfer the TRANS4 computed dimensions directly to a drawing. Software can be written to do this automatically, and TRANS4 has a DXF output option. The complete profile drawing is a better description of the elevations than a single point of reference.

TRANS4 Source File: G9721A1(Printed from Editor) Page: 1
Date6/ 8/97 By JTHCase G9721 Roll A Frame I Run 1 Plot P 0.50L
Comments:Photo Units inches +/- 0.010Real Units inches
Normal view of front wheel, red machine

C1=-3.0593530E+01 C2= 6.9243280E+00 C3= 6.4313090E-02 C4=-4.0188200E-03
C5= 3.7759250E-03 C6=-3.8870680E+01 C7=-6.4311910E-02 C8= 6.8385610E+00

Pt. No.	NAME	MEAS. Xp	- PHOTO Yp	MEAS. Xr	- REAL Yr	COMPUTED Xc	REAL Yc	COORDINATES Dx	Dy
1	ORIGIN	4.36	5.72	0.00	0.00	-0.0	-0.0	0.1	0.1
BP	R1	5.95	5.74	11.00	0.00	11.0	0.0	0.1	0.1
BP	R2	4.35	7.35	0.00	11.00	-0.0	11.0	0.1	0.1
BP	R3	2.76	5.71	-11.00	0.00	-11.0	0.0	0.1	0.1
BP	R4	4.38	4.12	0.00	-11.00	-0.0	-11.0	0.1	0.1
6	R5	4.39	3.88	0.00	-12.80	0.1	-12.7	0.1	0.1
7	R1A	5.95	5.71	11.00	0.00	11.0	-0.2	0.1	0.1
8	R2A	4.37	7.34	0.00	11.00	0.1	10.9	0.1	0.1
9	R3A	2.76	5.74	-11.00	0.00	-11.0	0.2	0.1	0.1
10	R4A	4.36	4.13	0.00	-11.00	-0.1	-10.9	0.1	0.1
11	R5A	4.36	3.88	0.00	-12.80	-0.2	-12.7	0.1	0.1
12	P1	8.79	4.41	0.00	0.00	31.1	-9.5	0.1	0.1
13	P2	9.15	4.46	0.00	0.00	33.7	-9.1	0.1	0.1
14	P3	8.72	4.50	0.00	0.00	30.6	-8.8	0.1	0.1
15	P4	8.88	4.31	0.00	0.00	31.8	-10.2	0.1	0.1
16	PROFIL	9.36	4.46	0.00	0.00	35.2	-9.2	0.1	0.1
17		8.80	4.41	0.00	0.00	31.2	-9.5	0.1	0.1
18		8.37	4.37	0.00	0.00	28.1	-9.7	0.1	0.1
19		8.01	4.29	0.00	0.00	25.6	-10.2	0.1	0.1
20		7.73	4.27	0.00	0.00	23.6	-10.3	0.1	0.1
21		7.43	4.27	0.00	0.00	21.4	-10.3	0.1	0.1
22		6.96	4.29	0.00	0.00	18.1	-10.1	0.1	0.1
23		6.66	4.30	0.00	0.00	16.0	-10.0	0.1	0.1
24		6.49	4.29	0.00	0.00	14.8	-10.0	0.1	0.1
25		6.26	4.26	0.00	0.00	13.1	-10.2	0.1	0.1
26		5.99	4.25	0.00	0.00	11.2	-10.3	0.1	0.1
27		5.70	4.22	0.00	0.00	9.2	-10.5	0.1	0.1
28		5.58	4.21	0.00	0.00	8.4	-10.5	0.1	0.1
29		5.49	4.18	0.00	0.00	7.7	-10.7	0.1	0.1
30		4.98	3.98	0.00	0.00	4.2	-12.0	0.1	0.1
31		4.40	3.92	0.00	0.00	0.1	-12.4	0.1	0.1
32	WHITU	10.31	6.04	0.00	0.00	42.0	1.8	0.1	0.1
33		7.43	6.01	0.00	0.00	21.4	1.8	0.1	0.1
34	WHITL	7.43	6.01	0.00	0.00	21.4	1.8	0.1	0.1
35		10.31	6.00	0.00	0.00	42.0	1.5	0.1	0.1
36	YELU	6.75	7.25	0.00	0.00	16.6	10.3	0.1	0.1
37		10.50	7.30	0.00	0.00	43.2	10.5	0.1	0.1

Figure 6

3. The third case is an example that was part of an extensive reconstruction project. The drawing of Figure 7 is worth a thousand words to explain what happened. The primary issue was the initial speed of car #1. The tire marks it left on the roadway in the north-bound lanes proved to be very helpful in this regard, once their locations on the roadway were determined. The problem was that scene features that could be seen in photographs were related to construction, and were not available to survey years after the incident. Their locations east-west could be determined, but their locations north-south could not be measured.

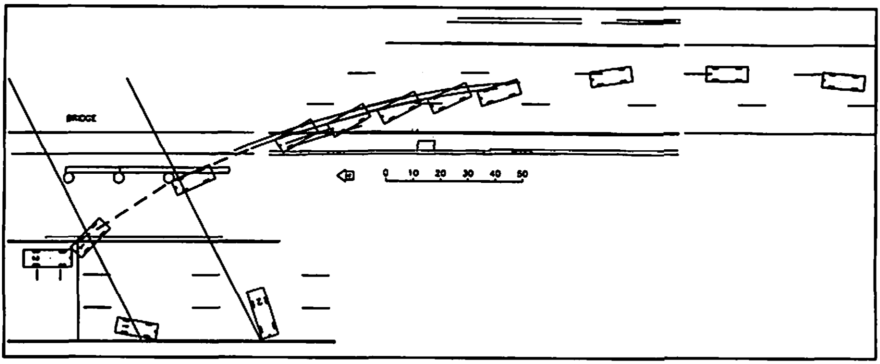

Figure 7

Several photographs were taken from the bridge looking down on recent pavement toward the south, none of which contained all of the data needed in one view. Unfortunately, they are mostly black and would not reproduce here. Three photographs had to be analyzed separately and the data combined to determine the location of the marks. The two taken from the bridge were labeled A12 and B11, and the fields used in the study are shown in the outlined areas in Figure 8. A photograph labeled C11 was taken from ground level and clearly captured the north end of the tire marks.

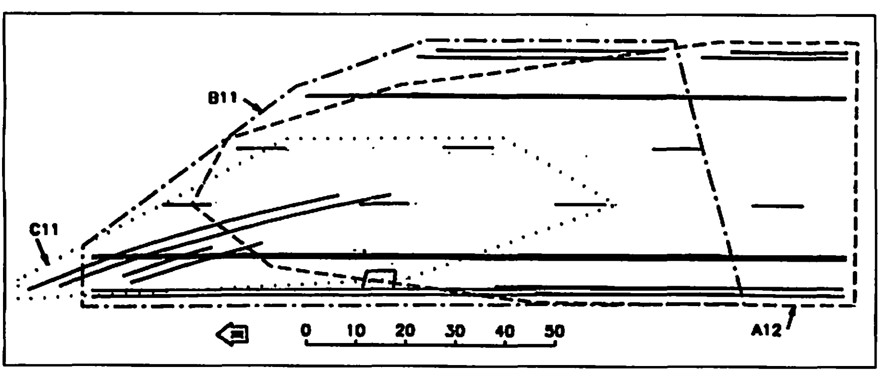

Figure 8

A construction paint mark near a drain was one point that could be seen in all three. The roadway lane widths were known, and the new lane stripes were expected to have been placed in nearly identical increments of close to 40 feet.

The first task was to digitize two of the views from the bridge, and to experiment with the stripe period lengths (BP real coordinates) until the features from one photo matched the same features in the other photo. When that was done, the third photograph taken from ground level and showing the north end of the tire marks was analyzed. These tire marks were added to the marks that could be seen in the other two, and all three sets overlaid almost without variance. The drain grate is shown skewed, which is a common result for a surface which is not on the plane - it has a different slope.

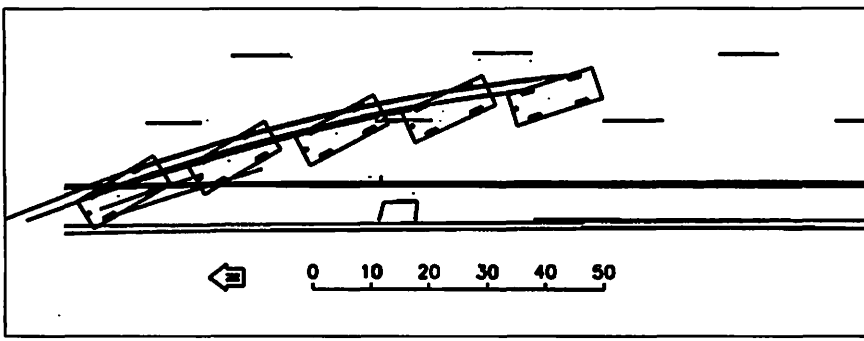

Figure 9

The path also matches a model of the car, so that a trajectory could be computed and its speed studied. The police measured a middle ordinate and computed a critical speed for the car. Funny thing! Such a middle ordinate could have been measured in only one place, for the right rear instead of the right front as reported, and right where the driver would have been changing steering and applying brakes. The police also reported calculating a radius of 272 feet, where the path radius measured 262 feet initially, 376 feet in the middle, and 363 feet near its north end. An EDSVS simulation reported a similar but continually changing radius for this travel.

The police reported using a drag sled to measure 0.86 Cf. In the EDSVS simulation study, sliding friction was varied from 0.65 to 0.86, with higher friction causing more "bow" to the path. The path matched the marks best with sliding friction of 0.72. Interesting! If your data is sufficient, and you look for it, the prevailing coefficient of friction may be computed.

Conclusion

It was mentioned earlier that knowing how to use photogrammetry might cause you to change the way you collect scene evidence. Concrete highways usually have 12x15 foot grids that are captured right in your photographs. You might apply paint marks near (not on) evidence you want to capture, or measure suitable points that will exist in your photographs, just in case you need them later. You could also try to take normal views of the side of a car which includes dimensions that you have measured. If doing this sort of thing keeps you out of fast moving traffic for just a little, or lets you recover dimensions which are later unreadable, it will be worthwhile.

When you get a case that is already four years old, photogrammetry may be the only way to gather the evidence you need.

References

1. Baker, J. S., "Traffic Accident Investigation Manual", p. 318, The Traffic Institute, Northwestern University, Evanston, IL, 1979
2. Kinney, J. R. & Magedanz, W. H., "TRANS4 and TRANSMRG - Photogrammetry Programs for Accident investigation", User's Manual, Kinney Engineering Inc., Corvallis, OR, 1987

Appendix A

Reference [1], Section 5, pp. 1-2, Theory and additional references.

Kinney Engineering, Inc.
2107 NW Fillmore
Corvallis, OR 97330
541-757-0349

5. THEORY

This section dicusses the theoretical basis of the photogrammetric transformation.

5.1. THE FOUR-POINT TRANSFORMATION

Mathematical derivation of the formula for the transformation is shown in Hallert [1][1] for the general case, and the formula is shown by Baker [2] and Bleyl [3] with specific application to traffic accident investigation. Others [4 through 7] have shown more refined applications. The transformation, which involves eight coefficients, may be written as follows:

$$X_C = \frac{C_1 + C_2X_P + C_3Y_P}{C_4X_P + C_5Y_P + 1} \qquad (5\text{-}1)$$

$$Y_C = \frac{C_6 + C_7X_P + C_8Y_P}{C_4X_P + C_5Y_P + 1} \qquad (5\text{-}2)$$

where:

X_C and Y_C = computed coordinate values in the real world,
X_P and Y_P = coordinate values on the photograph face, and
C = coefficients of the transformation.

The derivation assumes that the coordinate systems are orthogonal, i.e.the X and Y axes are perpendicular and that all points lie on the x-y plane.

5.2. Determining the Coefficients

5.2.1 The Formula

One method for determining the values of the coefficients is developed by expanding Eqs. (5-1) and (5-2) to obtain two equations which are linear with respect to the C coefficients, and then substituting known real values, X_R and Y_R, for the computed values, i.e.:

$$C_1 + C_2X_P + C_3Y_P - C_4X_PX_R - C_5Y_PX_R = X_R \qquad (5\text{-}3)$$

$$C_4X_PY_R + C_5Y_PY_R - C_6 - C_7X_P - C_8Y_P = -Y_R \qquad (5\text{-}4).$$

Then for any point with known X and Y values in both the real and photo coordinate systems, the C coefficients are the only unknowns in Eqs. (5-3) and (5-4). Since there are 8 unknown C coefficients, a solution to the linear system can be obtained if 8 independent equations can be found. This requirement is met if both the real and photographic X and Y values of 4 different BASE POINTS are known and no three of the points lie on a straight line in either coordinate system. Substitution of the known X and Y values for the 4 points, into Eqs. (5-3) and (5-4) yields a set of 8 linear equations.

5.2.2 The Algorithm

In TRANS4, the 8 coefficients are obtained by the standard Gauss' elimination method, with partial pivoting, applied to the set of 8 linear equations. TRANS4 also checks the magnitude of the pivot elements of the matrix and halts the computation with an error message if any pivot element is smaller than 1.0 E-10. When three BASE POINTS lie close to a straight line, two of the equations will be nearly identical and will produce very small pivot elements which affects the accuracy of the

1 Numbers in brackets correspond to references in Section 5.5

Appendix A

solution. The check on pivot elements is intended to avoid gross errors in the computation that would otherwise be caused by truncation errors. After the coefficients are computed the real coordinate values for other points located on the photograph surface are computed using Eqs. (5-1) and (5-2).

5.3. The Inverse Transformation Formula

In some cases it is useful to be able to do the inverse transformation and compute the photograph locations of selected points in the real world, e.g. where the point of impact noted on the police report would appear on a specific photograph. TRANS4 provides this option using equations developed by rearranging Eqs. (5-1) and (5-2) to obtain Eqs. (5-5) through (5-8).

$$X_P = \frac{(C_6 - Y_R)A - (C_1 - X_R)B}{(Y_R C_4 - C_7)A - (X_R C_4 - C_2)B} \qquad (5\text{-}5)$$

$$Y_P = \frac{(C_1 - X_R) - X_P(X_R C_4 - C_2)}{A} \qquad (5\text{-}6)$$

$$A = (X_R C_5 - C_3) \qquad (5\text{-}7)$$

$$B = (Y_R C_5 - C_8) \qquad (5\text{-}8)$$

5.4. The Computer Code

TRANS4 performs the transformation and inverse computations by means of the PASCAL program code listed in Section 9.

5.5. REFERENCES

1. Hallert, Bertil, Photogrammetry, pp. 9-16, McGraw-Hill Book Company, Inc., N.Y., 1960.

2. Baker, J. Stannard, Photogrammetry for Traffic-Accident Investigation., pp. 20-24, Northwestern University Traffic Institute, Evanston. Il, 1985.

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Appendix A continued