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A Non-Metric Close-Range Photogrammetric System for Mapping Geologic Structures in Mines

Field techniques, data reduction procedures, and results are described.

(Abstract on next page.)

Introduction

The Illinois State Geological Survey is investigating geologic strata and structures that could be used to predict unstable conditions in coal-mine roofs. Sites at which roof falls have already occurred are being studied to obtain evidence that might point to such predictors. At each site, roof stratification and structural features are examined in detail, and orientation of the natural surfaces, particularly bedding, fracturing, and shearing surfaces, must be measured. When conventional field techniques, such as measurements with the Brunton compass, are used, the task of obtaining substantial amounts of field data can be overwhelming, especially when the sites to be measured are hazardous places. In an effort to mitigate the work involved, we have tested a photogrammetric method for data acquisition and found it a useful tool in geologic field work.

Close-range photogrammetry has been used previously for obtaining data for geologic mapping[2, 3, 6, 9, 13, 17, 18, 19]. Terrestrial photogrammetry has been applied in strip mining as a surveying technique for planning, for instance, to determine volumes of rock earth masses[17, 18, 21]. Most terrestrial photogrammetry has used the analogue or semi-analytical approach, which requires the use of metric cameras to obtain acceptable results. Close-range photogrammetry also has been used for the collection of structural geologic data, but in the studies we are aware of[2, 3, 6, 9, 13, 19] expensive and rather cumbersome metric cameras have been employed. We believe this has been a major reason for the lack of general acceptance of this method of obtaining data. In order to overcome the drawbacks of the system as it has been used, we used a 70-mm non-metric camera and in one of the tests also a 35-mm amateur camera, in combination with a computerized, completely analytical approach.

Because photogrammetry shortens the time required for making measurements, it gives the geologist more time for evaluating the geologic significance of single structural elements in relation to the over-all structure. In addition, while the Brunton compass is restricted to measuring surface orientation of structural elements, the photogrammetric method also can be used to measure the spacing of fractures, thickness of beds, and shapes of bodies. The photographs furnish a complete permanent record that can be retrieved and analyzed at any time. Photogrammetry also may be the only practical means of acquiring data in areas of roof falls of high-walls of strip mines or quarries.

Geological Background

A significant aspect of our study of structural geologic features of the Herrin (No. 6) Coal Member and associated rocks in Illinois is the collection of data on stratification and fracturing in roof falls and other exposures. This involves numerous measurements of surfaces of bedding, jointing, cleating, faulting, and shearing. Linear structural elements, in particular striations, which are an indication of movements along structural surfaces, also must be recorded.

Conventionally, all these data are collected in the field with a Brunton compass. The portrayal of the spatial distribution of the surfaces and linear elements is often difficult, if not impossible. Lists of their orientations (strike and dip, Fig. 1), regardless of their relative position in space, must suffice. They are quite satisfactory as long as the distribution of the structural elements at the study site is homogeneous. To display such spatial information graphically, geologists use various techniques. Geologic maps and Schmidt nets[20] are the preferred display methods.

The Schmidt equal-area net of the lower hemisphere is a versatile and commonly used analytical tool (See Fig. 2). Available computer programs can manipulate structural data as required and display the results in a Schmidt net[3, 5, 10, 12, 14].

Object-Space Control

In using stereometric cameras or a phototheodolite to take photographs, the elements of exterior orientation at the time of exposure can be determined within certain limits. However, by reducing the photographic data acquisition system to a simple non-metric camera, as we did, a method of determining the exterior orientation must be established. This is accomplished with an object-space control system. Coordinates of control points in the object-space reference system are used to perform the resection and to establish exterior orientation.

To be practical, a control object must:

1. Take a short time to set up;
2. Be lightweight and easily transportable;
3. Be capable of changing size, depending on site conditions; and
4. Provide sufficient points for redundancy in the least squares solution.

With the above specified criteria, object-space control was provided by aluminum bars which were assembled, using bolts and nuts, to form 8 cubicals which were then connected to form a three-dimensional skeletal structure (frame). One-fourth-of-an-

Abstract: *The collection of structural data in mines is an integral part of the search for geologic indicators of mine-roof instability. We used close-range photogrammetry in conjunction with conventional geologic field methods to collect the necessary data. Stereopairs of photos were taken with 70-mm and also with 35-mm non-metric cameras. The structural geologic data were acquired and displayed by a computerized, analytical approach. Object-space control was obtained by using a modular aluminum frame consisting of eight cubic sections that can be assembled in various configurations. Photocoordinates were measured with a stereocomparator and reduced by the Direct Linear Transformation (DLT) method, which involved 11 transformation unknowns for each photograph. The least-squares method was used to determine the equations of the planes, using four to ten point measurements for each plane. The four tests described in this paper show that an analytical photogrammetric system utilizing a small-format non-metric camera meets the accuracy requirements of geological work, and that the method is not only technically feasible but in fact practical to use in geological mapping.*

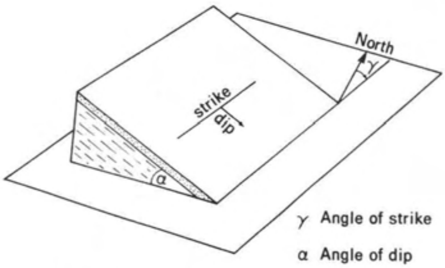

FIG. 1. Geologists determine the spatial orientation of any structural surface (e.g., bedding, fracturing, shearing) by its "strike," which is the azimuth of a line made by the intersection of an inclined surface and the horizontal, and by "dip", which is the maximum vertical angle made by the inclined surface and the horizontal. Direction of dip (eastward in the figure) must be given to define fully the spatial orientation of the plane.

inch diameter holes were precision drilled at predetermined positions 12 inches apart at the ends and in the center of each bar. The holes serve a dual purpose; they are used in assembling and attaching the cubic sections, and the center of the bolts and holes in the assembled structure provide three-dimensional object-space control points at increments of 12 inches in X, Y, and Z. The assembly of the skeletal structure is done in

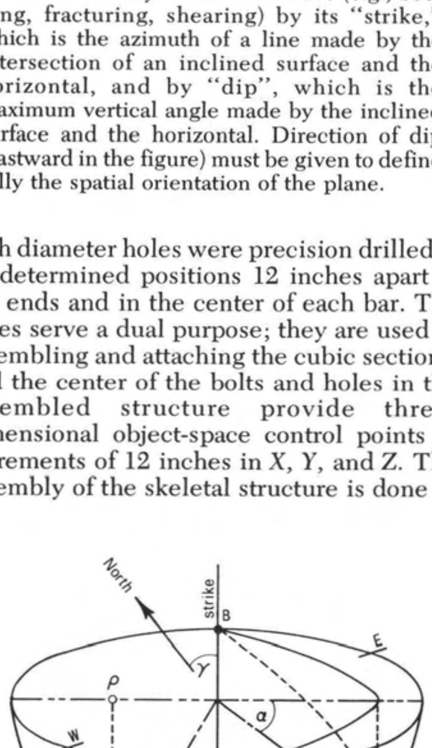

FIG. 2. Method of portraying the orientation (strike and dip) of a plane on a projection of the lower hemisphere (Schmidt net, 20). A normal to plane ABC with strike (γ) and dip (α) is projected onto the lower hemisphere and then to "pole" p. Plane ABC approximately corresponds in strike and dip to the bedding plane of Figure 1.

a matter of minutes in the mine. When assembled, each face of a cubic section contains a 3-×-3 matrix of control points. During preparation of the control frame components in the workshop of the Civil Engineering Department, care was exercised to maintain orthogonality of the assembled cubes. However, because the accuracy requirements of the final outputs were quite liberal, no special tests were made to determine the orthogonality of the completely assembled frame.

ACQUISITION OF PHOTOGRAPHY

A tripod-mounted 70-mm Yashica, model C, camera, net image format 55-×-55 mm, equipped with a Yashikor 80-mm, f/3.5 lens, and a hand-held 35-mm Canon camera, model FT, net image format 35×-24 mm, equipped with a 50-mm, f/1.2 lens, were used to test the feasibility of using small-format non-metric cameras. Stereopairs were exposed with camera optical axes nearly parallel to each other and approximately normal to the base line between exposure stations. A base-to-distance ratio of about 1:3 provided an overlap of more than 60 per cent.

DATA REDUCTION

Observations were made on the original negatives with a Wild STK stereocomparator and reduced by the analytical approach. The Direct Linear Transformation (DLT) approach[1] was used to establish the relation between the measured comparator coordinates and the object-space coordinates of the points. The following equations are used for this transformation:

$$x = \frac{l_1 X + l_2 Y + l_3 Z + l_4}{l_9 X + l_{10} Y + l_{11} Z + 1}$$

$$y = \frac{l_5 X + l_6 Y + l_7 Z + l_8}{l_9 X + l_{10} Y + l_{11} Z + 1}$$

where:
x, and y are coordinates of an image point X, Y, and Z are object-space coordinates of the point, and l_1 through l_{11} are DLT parameters.

For each photograph, 11 transformation unknowns are involved. Using single prime (′) for the left photo of a stereopair and double prime (″) for the right photo, the following relations are obtained for each point measured[10]:

$$(l'_9\, x' - l'_1) X + (l'_{10}\, x' - l'_2) Y + (l'_{11}\, x' - l'_3) Z + (x' - l'_4) = 0$$

$$(l'_9\, y' - l'_5)\, X + (l'_{10}\, y' - l'_6)\, Y + (l'_{11}\, y' - l'_7)\, Z + (y' - l'_8) = 0$$

$$(l''_9\, x'' - l''_1)\, X + (l''_{10}\, x'' - l''_2)\, Y + (l''_{11}\, x'' - l''_3)\, Z + (x'' - l''_4) = 0$$

$$(l''_9\, y'' - l''_5\, X + (l''_{10}\, y'' - l''_6)\, Y + (l''_{11}\, y'' - l''_7)\, Z + (y'' - l''_8) = 0$$

From these four equations the object-space coordinates (X, Y, and Z) of the observed points are computed. A fully documented computer program of the DLT method has been completed by Marzan[15, 16].

Four to ten points are measured on each plane. After the object-space coordinates of each of the observed points have been determined, the least-squares solution of a plane passing through the points is derived. From the coefficients of the equation of the plane, the geological components (strike and dip, Figure 1) of the orientation of the plane can be established by

$$P_1 X + P_2 Y + P_3 Z = 1,$$

the general equation of the plane in object space, where

$$\text{Strike} = 90?0 - \tan^{-1} (P_1/P_2),$$

$$\text{Dip} = \tan^{-1} \frac{(P_1^2 + P_2^2)^{1/2}}{P_3}$$

Test Cases

Four tests were made, three of them conducted outdoors in natural light and one underground in a coal mine. For each site, test planes that could easily be measured with the Brunton compass were placed in the area to be photographed. The control object was set up as close as possible to the area to be mapped. Three rotations were applied to the arbitrary reference system for alignment with geographic coordinate axes. To provide a basis for this rotation, the azimuth and tilt of the control frame were measured with the Brunton compass.

The first test was performed to determine the technical feasibility of the method. A permanent wooden structure at a playground site was selected because it provided rigid, well-defined planes of various orientations. Ten planes were measured several times with the Brunton compass, and stereopairs were taken with both the Yashica and Canon cameras.

Figure 3 shows the layout of the first test site and Table 1 presents results on strike and dip of the 10 planes.

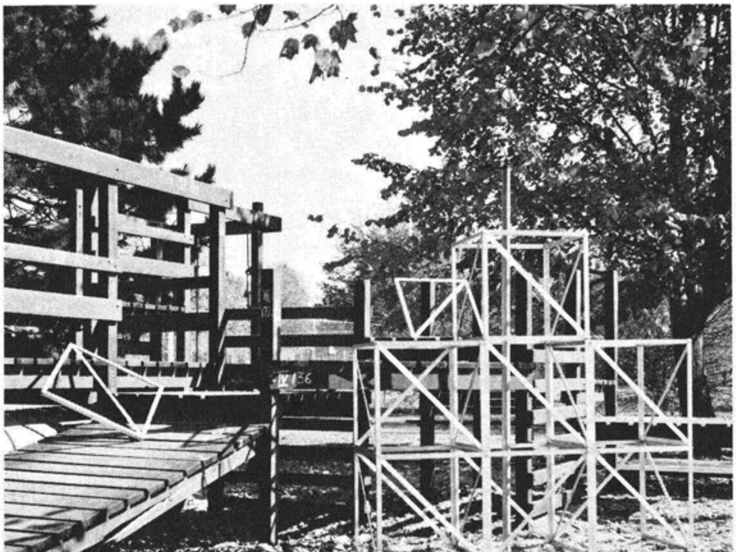

Fig. 3. A playground structure at Blair Park, Urbana, was used to test the newly developed aluminum frame of cube modules for object-space control. The quarter-inch diameter holes in each element are 1 foot apart and form a 3×3 matrix. Most of the structure planes measured are visibly marked by white chalk.

TABLE 1. RESULTS FROM TEST NO. 1

Column No. (1) Plane No.	(2) Brunton Strike/Dip (degrees)	(3) Yashica Strike/Dip (degrees)	(4) Canon Strike/Dip (degrees)	(5) Space angle* between Brunton Yashica	(6) Space angle* between Brunton minimum and maximum
1	170/14 W				
	171/14 W				
	167/14 W				
	172/13 W				
	176/15 W				
	173/15 W				
	172/16 W				
	173/15 W				
mean	171/14 SW	163/13 SW	163/13 SW	3°	5°
2	86/90				
	86/90				
	84/89 S				
	86/90				
	85/89 S				
	81/90				
mean	84/90	82/89 N	82/89 N	2°	5°
3	176/89 E				
	177/89 E				
	178/90				
	177/90				
	173/90				
	172/89 E				
	171/89 E				
	172/90				
mean	174/90	173/90	172/90	1°	7°
4	136/89 SW				
	135/89 SW				
	134/88 SW				
	142/90				
	131/89 SW				
	131/88 SW				
	136/90				
mean	134/89 SW	127/90	126/90	7°	5°
5	89/90				
	92/89 S				
	96/89 N				
	94/90				
	89/90				
	89/90				
mean	91/90	83/89 NW	83/85 SE	7°	7°
6	89/88 N				
	90/89 N				
	89/88 N				
	91/89 N				
	89/89 N				
	90/88 N				
	91/88 N				
	86/90				

TABLE 1. CONTINUED

mean	88/89 N	83/87 N	82/90	5°	5°
7	82/17 S 86/18 S 87/17 S 84/16 S 83/17 S 89/17 S 87/19 S 87/19 S				
mean	86/17 SE	not visible	80/18 SE	2°	5°
8	90/90 90/90 89/89 N 89/90 89/89 N 91/90 90/90 89/89 S 87/90				
mean	89/90	84/88 N	81/89 N	6°	4°
9	101/42 SW	97/40 SW	94/42 SW	4°	Single Brunton
10	127/53 SW	126/53 SW	127/53 SW	1°	measurements only

* The angle in space between the two results of plane orientation arrived at by averaging the Brunton measurements and by photogrammetry from the Yashica negatives has been determined graphically in the Schmidt net. For comparison, the space angle between the extreme Brunton measurements in each of the eight sets is given in column 6.

A comparison of the results obtained by the Yashica camera to those obtained by the Canon camera (columns 3 and 4 in Table 1) indicate that both systems yielded essentially the same results. However, it should be noted that the identification of the planes on the 80-mm-focal length photography (Yashica) was much easier than on the 50-mm-focal length photography (Canon), because of the former's larger photo scale. Since no other lenses for the Canon camera were available to this project, this camera was not used in any further test in this project. More experimentation will be needed on the matter of optimum photo scale and also on the use of 35-mm cameras.

In order to compare the accuracy of the photogrammetric system used with that of the Brunton compass approach, a second test at the same playground was performed. In this second test only one camera (Yashica-C) was used. The orientations of individual test planes were measured by ground surveying methods and used as a standard. Two reference points were selected near the test wooden structure. Solar observations were made to determine the azimuth of the line between the two selected reference points and the distance was measured with a steel tape. The horizontal positions of at least four points on each test plane were determined by intersection using a Wild T2 theodolite. The elevations of the points were determined by classical leveling techniques using a Zeiss NI2 automatic level. Each of the 8 test planes was fitted to the measured points on it by the method of least squares, and the orientation of each plane was then determined. The orientation of each test plane also was determined as the mean of five independent measurements with the Brunton compass as well as from photogrammetric measurements. The results of this test are given in Table 2. Columns 5 and 6 give an indication of the accuracy of each of the systems used.

The site for the third test was in an underground coal mine in east-central Illinois. The major purpose of this test was to find an illumination technique. In many instances, mining safety regulations prohibit the use of flash attachments unless the particular site is located along a main fresh-air corridor. We illuminated the subject to be photographed by scanning the area with head lamps during a time exposure. Additional tests must be

TABLE 2. RESULTS FROM TEST NO. 2.

Plane No. **	Survey Data Strike/Dip (Degrees)	Brunton Compass Strike/Dip (Degrees)	Photogrammetric (Yashica) Strike/Dip (Degrees)	Space Angle* between Survey and Brunton Results	Space Angle* between Survey and Photogrammetric Results
1	90/90 SE	105/90 SE	91/89 SE	15°	1°
2	88/89 SE	88/90	88/88 SE	1°	1°
3	135/89 SW	155/88 SW	132/87 SW	20°	4°
4	171/13 SW	164/13 SW	169/12 SW	2°	1°
5	88/89 NW	88/90	89/88 NW	1°	1°
6	85/15 SE	84/18 SW	89/15 SE	3°	1°
7	84/90 SE	83/89	85/88 SE	2°	1°
8	168/10 SW	168/13 SW	169/13 SW	3°	3°

* The space angle was determined graphically in the Schmidt net.
** Because measurement of the strike and dip of horizontal or almost horizontal surfaces is difficult and prone to error if measured by the Brunton compass, no horizontal test planes were included in this test.

made in this area to determine the illumination that will provide the best contrast on the coal surfaces to be measured. An exposure for two minutes under five headlamps is shown in Figure 4. A comparison of the data obtained by measurements with a Brunton compass and with photogrammetry is shown in Table 3 and in a Schmidt net diagram in Figure 5.

For the fourth test, a site in a strip mine in western Illinois was selected. The object of this test was to measure at least 100 fracture planes in the coal (cleats) with the Brunton compass and also photogrammetrically (us-

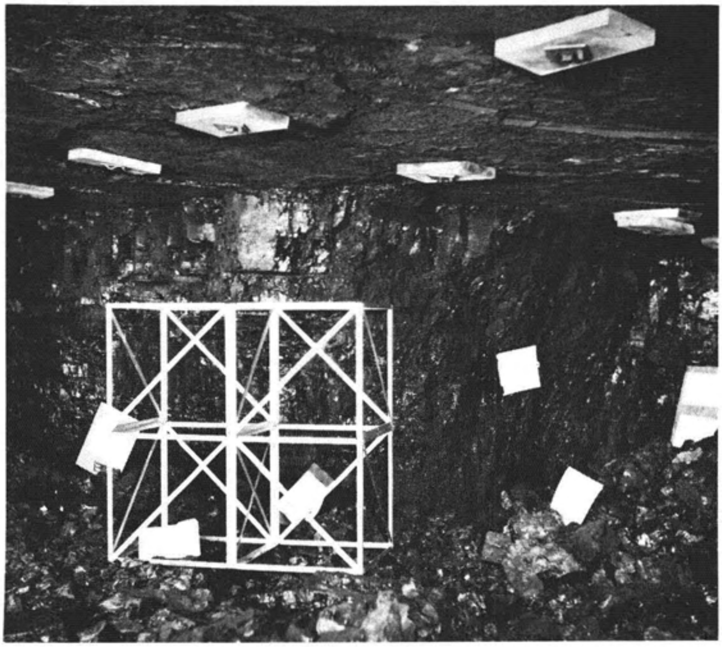

FIG. 4. The aluminum frame of four assembled modular cubic sections was set up in front of a coal face in an underground mine for object-space control. Several test planes were also placed into the study site. The rectangular boards near the top of the photo are the basal plates of roof bolts. Illumination was provided by scanning with five head lamps; exposure time was two minutes. The frame and test planes are slightly overexposed. Illumination on the strucutral surfaces in the coal is not optimal owing to an excess of reflection and lack of contrast. More experimentation will be needed to achieve optimal illumination in underground mines.

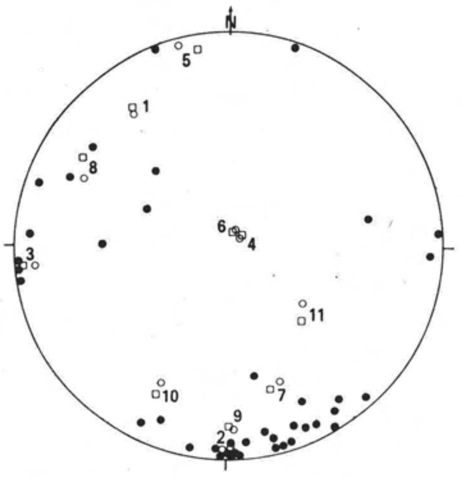

FIG. 5. A Schmidt net plot shows the results of both Brunton and photogrammetric measurements. The poles of 11 test planes at test site 3 agree well. The 40 poles of cleat surfaces are from photogrammetric measurements.

ing Yashica-C camera) and to compare the results.

Figure 6 shows the setting of test site 4, and Figures 7, 8, and 9 summarize the data obtained. A comparison of the two Schmidt net plots of structural planes measured both with the Brunton and the photogrammetric method shows very satisfactory agreement. Cleats that trend nearly parallel to the optical axes of the camera in its two positions, however, are very difficult to measure photogrammetrically ("blind range" in Figure 9). Because of this blindness, maximum V of the Brunton measurement (Figure. 7) is suppressed in the photogrammetric data (Figure 8), and maxima IVb and VI are distorted (compare Figures 7 and 8). In order to solve this problem, either the camera positions must be selected in such a way that the blind range will not lead to suppression of significant structural surfaces or a second stereopair of photos must be taken from a different direction.

In Figure 9 and in Table 4, the results obtained independently with the Brunton compass and the photogrammetric method are compared. Apart from the blind range mentioned above, the results are satisfactory. Note in particular that the orientation of the bedding planes could be measured photogrammetrically with a high degree of confidence although they could not even be measured with the Brunton because it is difficult to measure nearly horizontal planes. The distribution of the poles of the cleat surfaces in a girdle is almost congruent between the two independent methods, and maxima show little deviation from each other (Figure 9, Table 4), except of course, for the blind range.

CONCLUSIONS

It is not only technically feasible, but in fact practical, to use analytical close-range photogrammetric methods and a small-format amateur camera in geologic mapping. The accuracy desired for our purposes can be easily attained by using nonmetric cameras and a fully analytical approach. If

TABLE 3. RESULTS FROM TEST NO. 3.

Plane No.	Brunton Strike/Dip (Degrees)	Photogrammetric (Yashica) Strike/Dip (Degrees)	Space angle between Brunton and Photogrammetric Results (Degrees)
1	53/66 SE	54/69 SE	3°
2	91/85 NE	88/84 NE	2–3°
3	174/79 NE	174/86 NE	6°
4	136/5 SW	137/7 SW	2°
5	74/87 SE	80/83 SE	6°
6	114/7 SW	102/5 SW	1–2°
7	68/57 NW	73/59 NW	5°
8*	24/64 SE	31/69 SE	8°
9	82/75 NW	88/73 NW	2°
10	115/60 NE	115/66 NE	6°
11**	34/36 NW	44/40 NW	7°

* Plane 8 had somewhat unsteady support in broken coal.
** Plane 11 had insufficient contrast on surface.

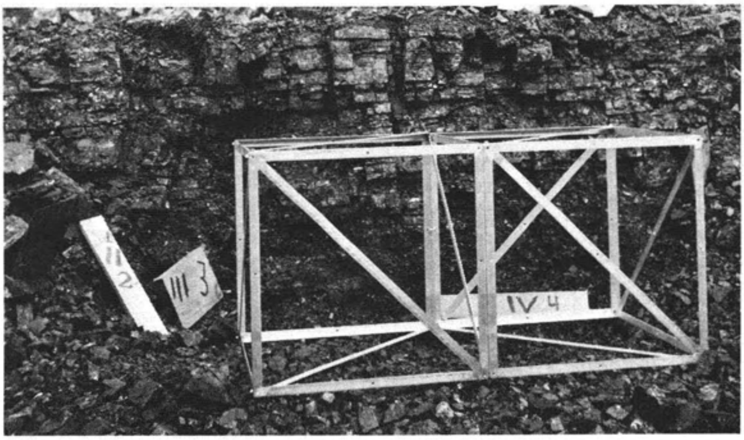

FIG. 6. Two modular cubes of the aluminum frame were assembled for test 4 in a strip mine. Eight test planes were placed into the study area. The coal seam is about 4-1/2 feet thick, with well developed cleating and bedding. Each of the 8 test planes was measured 5 to 6 times with the Brunton compass and 122 cleats were measured in the exposed coal face (Figure 7). Because measurement of the dip and strike of almost horizontal surfaces is difficult and prone to error, no bedding planes were measured with the Brunton compass.

more accurate results were required, the modeling of linear film deformations and lens distortions could be incorporated into the Direct Linear Transformation mathematical model. A more precise means of determining the orientation and orthogonality of the object-space control frame also could be chosen.

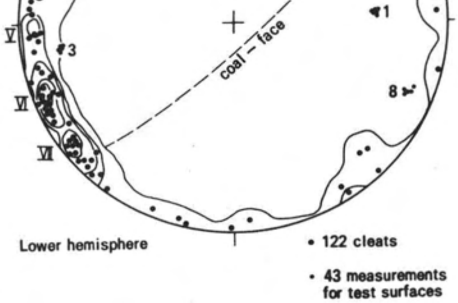

FIG. 7. Schmidt net plot of Brunton-measured cleats from coal face in Figure 6. Repeated measurements of the 8 test planes also are plotted. Distribution density of surface poles is shown by isopycnolines (lines of equal density) for better comparison with Figures 8 and 9. Braun's method[8] was used for drawing the lines. Maxima are identified by Roman numerals. Isopycnolines: 0.8, 4.1, 6.6, 10.7, 12.3, and 17.2 per cent.

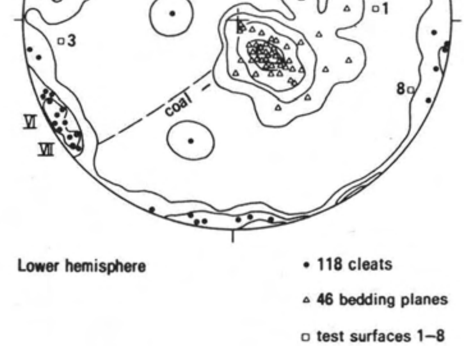

FIG. 8. Schmidt net plot of the 8 photogrammetrically measured test planes cleats, and bedding planes from coal face in Figure 6. Isopycnolines, maxima of poles, and orientation of the coal face are represented as in Figure 7. Isopycnolines: (a) bedding: 2.2, 6.5 17.4, 34.8, and 43.5 percent; (b) cleating: 0.8, 4.2, 6.7, 12.7, and 17.1 percent.

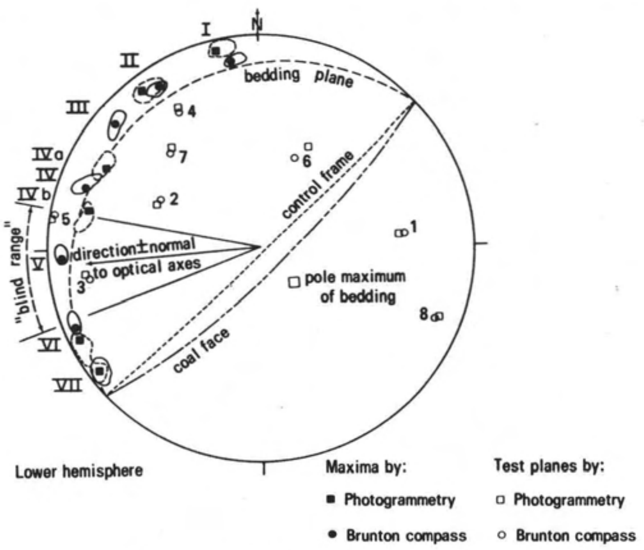

FIG. 9. Schmidt net plot of the results from the Brunton and photogrammetric measurements of structural data in test site 4 (compare Figures 7 and 8). Bedding maximum was about 47/18 NW; control frame front plane was 48/88 SE; coal face was about 48/82; tilt of control frame was 2° NW and 0.6° SW. Optical axes of camera and view are approximately from South to North (355°).

TABLE 4. SUMMARY OF RESULTS FROM TEST NO. 4.

a. Test planes

Plane No.	Brunton Strike/Dip (Degrees)	Photogrammetric (Yashica) Strike/Dip (Degrees)	Space angle* between Brunton and Photogrammetry (Degrees)
1	175/57 SW	175/55 SW	2°
2	27/43 SE	24/44 SE	2°
3	171/70 NE	173/72 NE	2–3°
4	60/63 SE	61/66 SE	3°
5	10/88 SE	9/89 SE	1°
6**	111/38 SW	116/45 SW	7°
7	48/52 SE	50/54 SE	3°
8	23/77 NW	22/78 NW	1–2°

b. Maxima of cleats

Maximum	Brunton Strike/Dip (Degrees)	Photogrammetric (Yashica) Strike/Dip (Degrees)	Space angle* between Brunton and Photogrammetry (Degrees)
I	82/78 SE	78/85 SE	9°
II	59/78 SE	54/82 SE	6°
III	42/79 SE	not distinguished	—
IVa		14/72 SE	9°
IV	20/76 SE		—
IVb		29/71 SE	7°
V	178/82 NE	not visible	—
VI	158/84 NE	154/84 NE	3°
VII	143/84 NE	144/84 NE	1°

* The space angle between the two results of plane orientation has been determined graphically in the Schmidt net.

** Plane 6 had somewhat unsteady support in broken coal.

Only in one test (No. 1), were both a 35-mm and a 70-mm camera used. While both cameras yielded essentially the same results (columns 3 and 4 in Table 1), the identification of planes was done much easier in the Yashica photography because of the larger photo scale (f-Yashica = 80 mm, f-Canon = 50 mm). More experimentation will be needed on the optimum photo scale and on the use of 35-mm cameras.

Even though it is fully expected that an analytical system utilizing a metric camera would yield more accurate results than a similar system using a non-metric camera, it is obvious that the use of the more accurate (and much more expensive) system could be justified only if the accuracy requirements warrant. It should be recognized that the accuracy requirements in geologic mapping are such that, frequently, a non-metric analytical photogrammetric system is sufficiently accurate. It should be emphasized that full details about the DLT approach and complete program documentation for it have been published by University of Illinois researchers[15, 16].

Should it become necessary to use a metric camera for data acquisition, we would recommend the DLT approach for analytical data reduction, to avoid the necessity of providing approximate starting values for the strike and dip of hundreds of planes such as would be required in the iterative analytical solutions.

The DLT mathematical model used in this project involves 11 transformation parameters, and thus requires a minimum of six (6) non-planar object-space control points imaged on each photograph of the stereomodel. These control points must be well-distributed throughout object space. Providing a healthy redundancy of object-space control (some 15→25 per cent more than the minimum requirement) would strengthen the solution and enhance the reliability of the final output. One must reduce extrapolation beyond object-space control points to a minimum. (The maximum allowable extent of extrapolation is a matter currently under theoretical and experimental investigations). Also, one must avoid having all object-space control points in one plane. As much deviation from the planar arrangement as can be allowed by depth-of-field considerations is highly recommended.

We have used close-range photogrammetry with a 70-mm non-metric camera in an analytical solution to collect information on the orientation of various kinds of geologic structural surfaces, such as cleats in coal, joints in the associated rocks, faults, spacing of fracture surfaces, and thickness and shape of various geologic bodies. An important advantage of the method is the preservation of the spatial relation of exposed structural surfaces, for instance, a roof fall in a coal mine, for future use. The method also can be used to map an advancing highwall in a strip mine to obtain structural data in sections a few tens of feet apart, which will ultimately make available a three-dimensional digital model of the form of the rock bodies.

Geologists could use this versatile and rather simple technique to collect data in roadcuts, quarries, and construction sites. The photogrammetric data would provide a complete and permanent record of many interesting but only temporary outcrops, and the data would be accessible for retrieval whenever needed.

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This paper is a slightly modified version of a paper entitled "Close-Range Photogrammetry for Mapping Geologic Structures in Mines," presented at the Symposium on Close-Range Photogrammetric Systems held in Champaign, Illinois, July 28–August 1, 1975.

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