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Development of a new digital photogrammetric technique for characterization of rock joint orientation

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Abstract: A new algorithm was developed to interpret joint orientations from a pair of images of the rock slope to overcome the limitation of photographing direction as in the parallel stereophotogrammetric system and to maximize the range of image measurement. This algorithm can be regarded as a modified multistage convergent photographing system. To determine camera parameters in the perspective projection equation that are the major elements in the photogrammetric technique, a new concept was developed by using three ground control points and single ground guide point. This method could be considered to be very simple when compared with other existing methods which use a number of ground control points and complicated analysis processes.

1. Introduction

The major parts of the input data for the design of rock slope construction are the items related with the rock joint especially the ones developed in the rock mass. It is because the stability of a rock slope has close relationship with existing geometrical structure of joints and their mechanical characteristics. The orientation data of rock joints can be collected from many sources, such as surface survey, borehole wall scanning, rock core examination and so on.

But there arise problems in the present surveying process, for examples, the materials from drilled core provide the restricted range of data, setting up the scanlines on the rock slope shows limitation of the surveying range in the scanline sampling, and impossible cases frequently occur when surveyor can not reach the accessible area (Priest, 1993). To supplement these kinds of problems, this study aims at developing a new method which introduces the vision-based three dimensional measurement technique as a tool in measuring joint orientation on the rock slope. This new method can be said as a modified multistage convergent photographing technique which contains three ground control points and one ground guide point.

2. Background

The analyzing method that extracts and interprets the quantitative characteristics of a space object by image has started from both the fields of photogrammetry and computer vision. In each field, many researches have been undergone respectively or under the same theoretical background for engineering application. There may be slight differences in terminology and in the analyzing methods according to the accuracy and the degrees of object recognition about the object shape between both fields (Hartley 1993).

The collinear condition equation is applied in both photogrammetry and computer vision to induce three dimensional global coordinates from two dimensional image coordinates. The collinear condition can be defined as equation (1). In equation (1), **a** is a vector corresponding image coordinate, and **A** is a vector corresponding global coordinate. k is a scalar that is equal to the ratio of the length **a** to the length **A** and R is a rotation matrix (Moffitt 1980).

$$\mathbf{a} = kR\mathbf{A} \tag{1}$$

To constitute a collinear condition equation, the interior and exterior parameters of camera should be determined. The camera parameters present the location of camera and the photographing direction within a certain global coordinate system. These parameters should be determined in every time when the location or the direction of the camera is changed. Using the camera parameters, equation (1) gives,

$$\begin{bmatrix} x_a - x_0 \\ y_a - y_0 \\ -f \end{bmatrix} = kR \begin{bmatrix} X_A - X_L \\ Y_A - Y_L \\ Z_A - Z_L \end{bmatrix} \tag{2}$$

where X_A, Y_A, Z_A are the global coordinates of an arbitrary point A on the object and x_a, y_a are the image coordinates of the point a which is the projection of the point A on the image. Interior parameters are the focal length f of the camera and principal point (x_0, y_0) of the image. Exterior parameters are rotation angle (ω, ϕ, κ) and translation vector (X_L, Y_L, Z_L), which constitute rotation matrix.

To determine the camera parameters, several methods are currently being used like resection method (Moffitt, 1980), DLT method (Abdel-Aziz, 1971) in photogrammetry and Tsai method (Tsai, 1986) in computer vision, respectively. These methods need a lot of ground control points whose global coordinates are previously known as input data. Generally, the optimized camera parameter can be determined by iterative calculation of the perspective projection equation using ground control points and initial guess of camera parameters. With each camera whose parameter has been determined, the global coordinate of object can be obtained by mixing images of same object photographed from different angle.

Among the various cases concerning photographing angle, the simplest one is the parallel stereophotogrammetry (Moffitt, 1980). This is a limited analyzing method for the special case with paralleled photographing direction, whose collinear condition equation determined by interior and exterior parameters can be simply converted into parallax equation. This can be regarded as a very simple analyzing method which has been actually applied to rock slope (Hagan, 1980, Ryu, 2000). But to solve the problems revealed from the cases of blind spot invisible on the image and to secure the largest analysis area, it is necessary to develop a new method which can fulfil the collinear condition equation in a generalized manner.

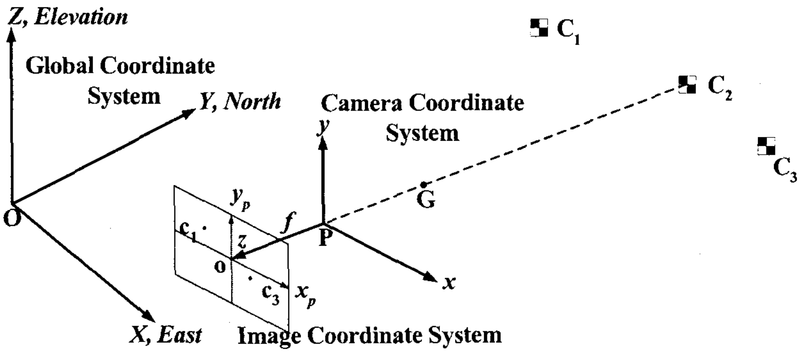

Figure 1. Geometrical layout with ground control points and guide point.

The new method developed in this study, which can analyze global coordinates from the images photographed from arbitrary direction, has a great advantage to overcome the limitation in photographing condition.

3. Analysis method

In order to apply generalized collinear condition equation (Atkinson, 1996), only three ground control points and one ground guide point were introduced under the multistage convergent photographing system. Figure 1 shows the relative relationship among the axes of global, camera and image coordinate system (Klette, 1998) and the geometrical layout of three ground control points (C_1, C_2, C_3) and one ground guide point (G).

Calculation of focal length and perspective center

Figure 2 is the schematic diagram describing the photographing layout of the camera location, the ground control points and the ground guide point. In the figure 2, f is focal length, P is perspective center, o is principal point, C_1, C_2 and C_3 are ground control points and G is ground control point. The focal length can be calculated using the proportional relation of lengths between u_1 and u_2 in space and d_1 and d_2 in image as follows.

$$f = (s_1 - s_2)\left(\frac{d_1 d_2}{u_1 d_2 - u_2 d_1}\right) \qquad (3)$$

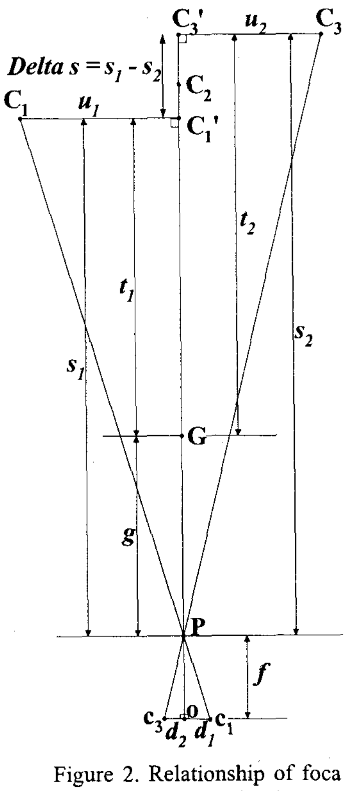

Figure 2. Relationship of foca length, ground control points an guidepoint.

The position of perspective center, which is translation vector, can be derived by using point G and line *I* that connects G and C_2, when *g* is the distance between ground guide point G and perspective center P as shown in equation (4) where *l, m* and *n* are the direction cosines of line *I*.

$$P_X = G_X - gl\ ,\ P_Y = G_Y - gm\ ,\ P_Z = G_Z - gn \tag{4}$$

Rotation matrix

The rotation matrix that determines the direction of camera can be derived from rotation angle of each axis in camera coordinate system. By applying ground control point and ground guide point, the rotation angle of each axis can be simply induced from the directional cosines of the line connecting the principal point of the image, the ground control points and the ground guide point.

Figure 3 presents the relationship between the amount of rotation of the image and the direction cosines in global coordinate system. The equation of axis of ray (line *I*) is,

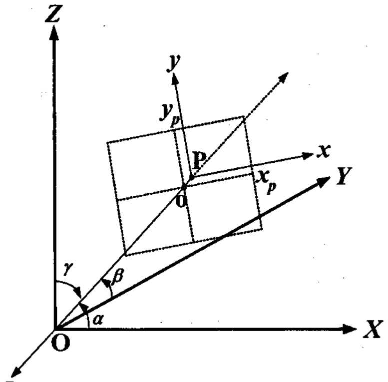

Figure 3. Rotation matrix by directional cosine.

$$I: \frac{x-a}{L} = \frac{y-b}{M} = \frac{z-c}{N} \Rightarrow \frac{x-a}{l} = \frac{y-b}{m} = \frac{z-c}{n} \tag{5}$$

where $L = kl,\ \ M = km,\ \ N = kn$. The direction cosines can be defined as follows.

$$\cos\alpha = l,\ \ \cos\beta = m,\ \ \cos\gamma = n \tag{6}$$

Constituting the rotation matrix using direction cosines gives,

$$R = \begin{bmatrix} \cos(x,X) & \cos(x,Y) & \cos(x,Z) \\ \cos(y,X) & \cos(y,Y) & \cos(y,Z) \\ \cos(z,X) & \cos(z,Y) & \cos(z,Z) \end{bmatrix} \tag{7}$$

The components of rotation matrix which have the same value with the direction cosines of line *I* are,

$$\cos(z,X) = l,\ \ \cos(z,Y) = m,\ \ \cos(z,Z) = n \tag{8}$$

The rotation matrix using rotation angles, ω, ϕ and κ can be written,

$$R_{\omega\phi\kappa} = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix} = \begin{bmatrix} \cos\phi\cos\kappa & \sin\omega\sin\phi\cos\kappa + \cos\omega\sin\kappa & -\cos\omega\sin\phi\cos\kappa + \sin\omega\sin\kappa \\ -\cos\phi\sin\kappa & -\sin\omega\sin\phi\sin\kappa + \cos\omega\cos\kappa & \cos\omega\sin\phi\sin\kappa + \sin\omega\cos\kappa \\ \sin\phi & -\sin\omega\cos\phi & \cos\omega\cos\phi \end{bmatrix} \tag{9}$$

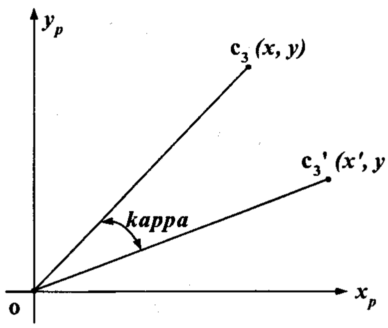

Figure 4. Determination of κ (c_3' is projected by ω, ϕ in equation (10) and κ=0).

From equation (7), (8) and (9), *l, m* and *n* are r_{31}, r_{32}, and r_{33}, respectively. So these values can be represented as $\sin\phi$, $-\sin\omega\cos\phi$, $\cos\omega\cos\phi$. Therefore, the rotation angle ω and ϕ can be obtained as in equation (10) from the direction cosines of line *I*.

$$\phi = \sin^{-1}(l)\ ,\ \ \omega = \tan^{-1}(-m/n) \tag{10}$$

The rotation angle κ in figure 4 can be obtained from the global coordinate of the ground control point C_1 and C_3 and their corresponding coordinates in the image as in equation (11). The sign of κ can be determined following the condition in equation (12).

$$\kappa = \cos^{-1}\left(\frac{xx'+yy'}{\sqrt{x^2+y^2}\sqrt{x'^2+y'^2}}\right) \tag{11}$$

where $\kappa < 0$ when $c_{3,y} > c_{3,y}'$, else $\kappa > 0$.

The whole components of the rotation matrix in equation (9) now can be completed using the results from equation (10) and (11).

Calculation of global coordinates

The collinear condition equations derived from left and right images are given in equation (12).

$$(X - X_L) = (Z - Z_L)A,\ (Y - Y_L) = (Z - Z_L)B,\ (X - X_R) = (Z - Z_R)C,\ (Y - Y_R) = (Z - Z_R)D \tag{12}$$

where,

$$A = \frac{[r_{11_L}(x_{a_L} - x_0) + r_{21_L}(y_{a_L} - y_0) + r_{31_L}(-f)]}{[r_{13_L}(x_{a_L} - x_0) + r_{23_L}(y_{a_L} - y_0) + r_{33_L}(-f)]} \quad B = \frac{[r_{12_L}(x_{a_L} - x_0) + r_{22_L}(y_{a_L} - y_0) + r_{32_L}(-f)]}{[r_{13_L}(x_{a_L} - x_0) + r_{23_L}(y_{a_L} - y_0) + r_{33_L}(-f)]}$$

$$C = \frac{[r_{11_R}(x_{a_R} - x_0) + r_{21_R}(y_{a_R} - y_0) + r_{31_R}(-f)]}{[r_{13_R}(x_{a_R} - x_0) + r_{23_R}(y_{a_R} - y_0) + r_{33_R}(-f)]} \quad D = \frac{[r_{12_R}(x_{a_R} - x_0) + r_{22_R}(y_{a_R} - y_0) + r_{32_R}(-f)]}{[r_{13_R}(x_{a_R} - x_0) + r_{23_R}(y_{a_R} - y_0) + r_{33_R}(-f)]}$$

X, Y and Z are the components of an arbitrary point on the object for analysis and (x_L, y_L) and (x_R, y_R) are the coordinates of the points projected on the left and right image, respectively. (X_L, Y_L, Z_L) and (X_R, Y_R, Z_R) are the components of perspective centers of both cameras. r_L and r_R are the components of rotation matrices of left and right camera, respectively. f is focal length and (x_0, y_0) are the components of the principal point of the image. Solving the four equations simultaneously for the unknowns X, Y and Z, we can have four X's, four Y's and two Z's. The global coordinates of target point can be the average value of each component, respectively.

Joint orientation could be determined by the normal vector of the joint plane, which can be induced from vector product among the vectors consisted by the three or more points arbitrary chosen on the joint plane. The global coordinates of the arbitrary points can be analyzed using the algorithm explained above.

4. Geometrical verification

The geometrical verification was executed to verify the propriety of this newly developed method.

For the first step, the collinear condition equation was constituted using the camera parameters, such as rotation angles, perspective center and focal length of left and right cameras, arbitrarily prepared and known according to the photographing setup for verification. Substituting the camera parameters in equation (12) and the coordinates of ground control points as input data, we can get the two dimensional corresponding coordinates on the image of each camera as results.

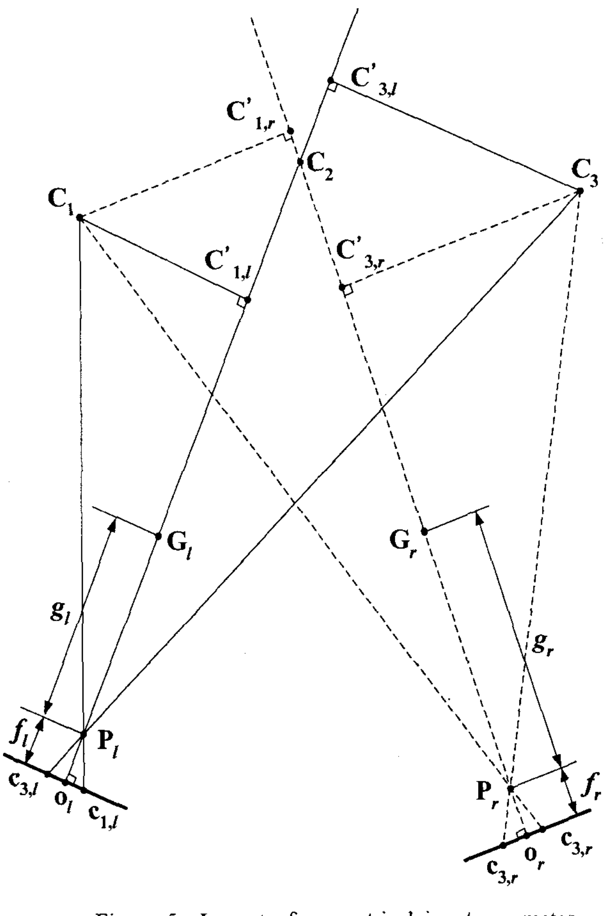

Figure 5. Layout of geometrical input parameter for geometrical verification.

The process for the second step is actually backward analysis to the first step. The camera parameters were induced according to this new method and using the two dimensional coordinates on the image as data, the global coordinates of ground control points were calculated as results.

The layout of the photographing setup for geometrical verification was shown in Figure 5 and the results were in Table 1. The results show very little difference. The largest error was occurred in *Y* direction (direction from camera to slope face) of which was under 2 mm. This amount of error can be regarded to have almost no influence in calculating joint orientation.

The whole sequence including the process of calculating joint orientation was coded using FORTRAN (F90) language which can be run under PC environment.

Table 1. Comparison of parameters that used geometrical verification.

Parameter		First step		Second Step		Difference	
		Left	Right	Left	Right	Left	Right
Control point (mm)	C_1	-2000, 4500, 1800		-2000.432, 4501.152, 1800.403		0.432, 1.152, 0.403	
	C_2	100, 5000, 2000		100.000, 4999.998, 1999.993		0.000, 0.002, 0.007	
	C_3	1800, 4800, 1500		1800.848, 4801.811, 1500.777		0.848, 1.811, 0.777	
Rotation angle (°)	ω	111.595	109.242	111.595	109.242	0.000	0.000
	ϕ	-22.136	16.848	-22.136	16.848	0.000	0.000
	κ	0.000	0.000	-0.002	0.005	0.002	0.005
Perspective center (mm)	P	-2000.0, 200.0, 100.0	1800.0, -300.0, 150.0	-2000.281, 199.355, 99.745	1800.521, -301.624, 149.433	0.281 0.645 0.255	0.521 1.624 0.567
Focal length (mm)	f	11.000	11.000	11.003	11.004	0.003	0.004
Ground guide point (mm)	G	.	.	-1057.983, 2353.181, 952.301	930.489, 2410.829, 1096.233	.	.
Length between *P* and *G* (mm)	g	2500	3000	2500.748	3001.798	0.748	1.798
Image coordinates of control point (mm)	c_1	-4.475, -0.005	-3.998, -0.044	.	.	.	.
	c_3	3.865, 0.605	4.914, 0.755	.	.	.	.

5. Conclusion

A new algorithm to interpret joint orientation was developed using a pair of rock surface images photographed by multistage convergent photographing technique. To apply generalized collinear condition equation which defines the relationship between three dimensional global coordinates of the slope face and two dimensional coordinates of its images, only with three ground control points on the photographing slope face and one ground guide point, newly introduced in this study, on the collinear line were introduced to determine the camera parameters. The calculation process could be regarded as a very simple one when compared with other analysis techniques.

Form the geometrical verification executed to verify the propriety of this newly developed method, maximum error occurred in *Y* direction (direction from camera to slope face) of which was under 2 mm. This amount of error can be regarded to have almost no influence in calculating joint orientation.

The whole sequence including the process of calculating joint orientation was coded using FORTRAN (F90) language which can be run under PC environment.

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