THE 3D MAPPING OF A TEXTURED SURFACE USING DIGITAL PHOTOGRAMMETRIC TECHNIQUES

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ABSTRACT:

The determination of three-dimensional (XYZ) co-ordinates of a textured surface, represented by densely spaced individual points, by means of digital photogrammetric techniques, is reported. The method is applied to the measurement of the three-dimensional changes that occur on the rock face in a deep-level underground mine, due to a pre-conditioning blast. Digital Photogrammetric techniques applied are discussed and a sample of the results is presented. The sub-millimetre accuracies required for the deformation analysis were achieved.

1. INTRODUCTION

The deep-level gold mines on the Witwatersrand (South Africa) are located at depths of over 3,000 m below surface. The gold ore is located in extensive tabular reefs, kilometres in extent, but only a few centimetres thick. Mining excavations are thus also tabular, hundreds of metres in extent, and less than 1 metre in height. The tabular shape of these excavations or panels, plus the large overburden, result in extensive mining induced stress changes in the rock mass surrounding them. With each advance of the mine face, sudden changes in the rock stresses occur. This results in sudden fracturing of the exposed surfaces of the excavation, with accompanied deformation. In some mining panels, it is desirable to "pre-condition" or soften the rock mass ahead of the face by pre-fracturing it with large blasts. This has the effect of pushing the critical stress field deeper into the rock mass, alleviating some of the fracturing and hazardous deformations in the vicinity of the excavation.

From a research perspective, it is desirable to quantify the deformations of the face due to blasts in order to better understand their effect on the fracture patterns that develop. Digital photogrammetry is an ideal method that can be employed to monitor these deformations. The necessary photogrammetric equipment is portable and easy to use underground, where conditions are extreme with temperatures as high as 40 deg C and humidity close to 100 percent. Digital photogrammetric techniques are highly accurate, and can be used to detect quite small three-dimensional changes. Furthermore, a digital elevation model, of the new fractures that develop on the face due to a blast, can be produced as part of the photogrammetric process.

The underground mining environment is especially hazardous and constrained, the typical working area is not higher than 0.5m to 1m and thus provides a good opportunity to demonstrate the flexibility and accuracy of digital photogrammetry in restrictive environments. This paper provides a brief description of the procedures followed in obtaining the desired measurements of the rock face to be evaluated and presents a sample of the results achieved in this regard.

In order to generate the three dimensional (XYZ) object space co-ordinates for the points of interest, which represent the surface to be mapped, the following steps were taken:

- Establishment of a Reference System
- Image Acquisition
- Camera Position Location
- Feature Extraction
- Image Matching
- Space Intersection
- Deformation Analysis

The details of each of these procedures are discussed in the following.

2. REFERENCE CO-ORDINATE SYSTEM

As in all deformation surveys, the maintenance of a reference co-ordinate system for the duration of the survey is paramount. Due to the nature of the underground mining environment, with limited access and severe instability, the design and testing of a maintainable co-ordinate system is of critical importance. In order to obtain the desired sub-millimetre accuracy, a complex configuration of co-ordinate reference points and camera stations is required. The photogrammetric design relies on two types of control points to maintain the reference co-ordinate system throughout the entire photogrammetric model, these are co-ordinated points on the reference frame and tie points (points required for the transfer of co-ordinate control from one stereo-image set to the next). These points must be configured to provide an adequate geometry to ensure accurate determination of the camera station positions and orientations and thus must be able to withstand the impact of the pre-conditioning blast.

In order to realise this objective, a stable reference co-ordinate system is required. The use of a pre-constructed reference frame, consisting of steel tubes and a steel back plate with attached circular retro-reflective targets to define the co-ordinate system, provides a means of achieving this. Due to the limitations of the mining environment, the maximum reference frame size tolerated is 0.5m x 0.5m x 0.2m.

The only stable structures within the stope (the working area at the rock face in the mine) which are capable of maintaining stability during the pre-conditioning blast, within the required accuracy, are the wooden packs which support the overhead "hanging wall". This poses a substantial problem as it restricts the reference co-ordinate frame, attached to a pack, to being placed at right angles to the rock face being measured. In order to compensate for the poor geometry and diverging imagery resulting from this, a complex configuration of control points is required for the establishment of accurate point co-ordinate on the rock face itself. Figure 1, below shows a diagrammatic description of the configuration required for transferring the co-ordinate system from the reference frame to the rock face.

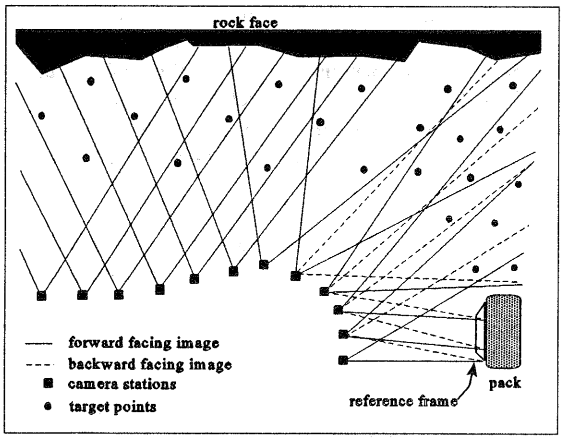

Figure 1 - Camera and Target Pole Configuration

The adopted design is based on the acquisition of images at two height levels. During the image acquisition, the camera is moved sequentially from station to station, beginning with the reference frame and following the wall until the entire deformation area is covered. Multi-images at each station are taken while transferring the co-ordinate system from the reference frame to the face, through an angle of 90 degrees.

During image acquisition the operator is faced with the difficult task of guaranteeing full multi-image coverage of the face, while hand-holding the camera in the physically very demanding and constrained environment.

3. IMAGE ACQUISITION

In the interest of maximum portability of the measuring system, it was decided to rely on the use of a digital still camera. This decision was taken after first attempts with a CCD video camera, linked to a frame grabber in the docking station of a laptop, proved extremely cumbersome and impractical. The Kodak DCS420m was found to be a suitable image capture device, both portable and able to withstand the harsh environment of the deep-level mine, while satisfying all safety condition for electronic equipment. The DCS420m has a solid state CCD sensor with a resolution of 1524 x 1012 pixels on a 14mm x 9.3mm chip (9μm x 9μm per pixel). This camera stores up to 65 black and white images on a single PCMCIA Type III hard drive (105Mb capacity); the drives are interchangeable and manufacturers claim the capture of up to 1000 images is possible on one battery charge.

Due to the constrained space available in the stope, a very wide angle lens is required to obtain the maximum field of view. For the photography, a 14mm lens was employed, which is the approximate equivalent of a 28mm lens with a conventional 35mm camera. As the CCD sensor only samples the centre part of the image created by the lens, the fish-eye distortion typical for a 14mm lens, at the image edges, has little negative effect and can be well modelled with the lens distortion model.

As there is no readily available power source in the stope, image lighting needs to be flash generated. For this purpose, the Nikon SB-20 Speedlight provided a more than adequate solution.

3.1 Pre-Site Preparations

Before entering the stope, it is necessary to pre-calibrate the camera and determine the co-ordinates of the reference control frames to be used.

3.1.1 Camera calibration must be carried out prior to entering the mine. Throughout the process of image capture the camera must remain at the fixed and pre-calibrated focal length. This is vital to the analysis of the data after image capture, as no self-calibration procedures are possible.

For the image capturing process, the camera must be focused to a suitable distance for the stope conditions. This typically varied between 1.5m and 2.5m depending on the closure within the stope. Once the focal length is set, the lens focusing ring is taped into position to prevent movement during the image capture process.

Calibration of the interior orientation parameters of the camera, including principal distance, principal point and lens distortion parameters, is achieved by the capture of multiple images of a calibration control frame, from differing perspectives. Semi-automated analysis of the calibration images by target centring and target identification algorithms (described below) and a constrained bundle adjustment provides the desired parameters.

3.1.2 Co-ordination of the reference control frame must be done prior the survey. The reference control frame defines the co-ordinate system for the stope and must thus be defined to the highest degree of accuracy. The following steps are taken in calculating the object space co-ordinates of the centres of the circular retro-reflective targets on the reference frame:

- Image Capture
- Distance Measurement
- Target Location and Identification
- Free Bundle Adjustment

The pre-calibrated camera is used to capture a series of images of the reference frame from differing perspectives. In addition to the images, the precise measurement of at least one distance between extreme target centres is required. This distance will provide the constraint of scale on the photogrammetric determination of the co-ordinates of the target centres. The precision of the distance measurement carried out with a micrometer was better than 0.5mm. This was sufficient in spite of the transfer of the scale from the small frame to the 10m rock face of the study case. It should be noted that the required accuracy refers to relative displacement in individual portions of the wall, as opposed to an overall absolute accuracy.

Target centres are then located by an image analysis process which calculates the centre-of-gravity of the pixel grey levels in a window defined around the target by a thresholding process. Identification of the target, i.e. the association of the targets with the correct number in the co-ordinate list, is semi-automated. An initial eight targets are manually identified, after which an automated identification process relying on a direct linear transformation (DLT) resection calculation locates the remaining control frame targets. This process relies on a list containing the co-ordinates of all control points, where initial estimates of their object space co-ordinates to the nearest centimetre are sufficient.

The final co-ordinates of the targets are calculated by means of a free bundle adjustment. Initial approximation of the exterior orientation parameters (perspective centre and rotation angles) are provided by the DLT calculation for the identification of the targets, as described above. The pre-calibrated camera parameters (principal distance, principal point and lens distortion parameters) are held fixed in the bundle solution.

3.2 Image Capture

Once in the stope, the reference co-ordinate system must be established and the camera prepared for use, before images can be captured.

As the environment of the stope is extremely hot and humid, an on-site acclimatization period is required for the equipment. In practise it was found that at least half and hour exposure to stope conditions was needed to free the camera lens and all electronic components of condensation

The reference co-ordinate system is established by attaching the reference control frame to a suitable support pack (Figure 1), at one end of the rock face to be measured. To achieve the geometric stability required for sub-millimetre determination of the rock face digital elevation model, a high degree of redundant images were captured. To cover the 10m long and 1m high rock face under investigation, a total of 60 images was taken, including those necessary for the transfer from the reference frame to the wall. In this way each surface point was covered by an average of 6 images. The pre-analysis showed that a sufficiently strong geometry for the overall image formation could only be guaranteed by a set of control points in front of the rock face. This was realised by introducing target poles with circular targets, evenly distributed in an area covering a band of approximately 1m ahead of the face. These points only functioned as tie points and could therefore be placed independently for the pre- and post-blast photography.

4. DATA PROCESSING

Once the images have been captured, both before and after the pre-conditioning blast event, the following steps are needed to extract the relevant rock surface co-ordinates for the deformation analysis.

- Camera Position Location
- Feature Extraction
- Image Matching
- Space Intersection

4.1 Camera Position Location

Before the features on the rock surface can be analysed, it is necessary to determine the location and orientation of the camera setups in object space, as defined by the reference co-ordinate system. These parameters, the exterior orientation parameters, $\omega/\kappa/\phi$ (rotation angles about the X/Y/Z axes) and $X_c/Y_c/Z_c$ (perspective centre object space co-ordinates of the camera's position) are determined by means of direct linear transformations followed by bundle adjustment calculations for each of the camera stations in turn.

4.1.1 Direct Linear Transformation (DLT): The initial estimation of the camera exterior orientation parameters and tie point positions are determined by means of a sequential "folding-out, folding-in" DLT model. In an initial step, at least six reference frame points are needed to determine the first camera position. The DLT employed for this stage provides exterior orientation parameters as well as the DLT transformation co-efficients. These transformation co-efficients are then used to evaluate the tie point positions which provide reference points for the next camera position. This resection-intersection sequence was originally intended to be executed throughout the whole model, until approximation values for all camera position and orientations are determined for a subsequent complete bundle adjustment. However, in practise, it proved necessary even at this preparatory stage to execute sub-block bundle adjustments for due to excessive error propagation.

4.1.2 Bundle Adjustment: The complete bundle adjustment includes all of the data in a combined adjustment and allows for the inclusion of the pre-calibrated interior orientation parameters of the camera as constraints to the adjustment; also held fixed are the reference frame co-ordinates.

Average precisions obtained over five full image sets of the area taken at different times and in different condition are:

σx	σy	σX	σY	σZ
(mm)	(mm)	(mm)	(mm)	(mm)
0.002	0.002	0.5	0.5	0.8

4.2 Feature Extraction

To generate a digital elevation model of the surface a dense cloud of points needs be extracted from the images. Such points can be found on the basis of changes in the texture of the image. They are automatically extracted from a "target" image by means of an interest operator after which conjugate points on the other images of the same scene are located by image matching.

4.2.1 Image Filtering: As some of the images may provide a too uniformly textured surface, in terms of their grey level contrast, they may need to be enhanced to provide greater contrast. This is best done using a High-Pass filter algorithm (Lim, 1984) so as to enhance the high frequency, edge components, of the image and filter out the low frequency, uniformly textured components. The result of the filtering process is an output image which is visibly sharper and contains greater localised contrast in image texture.

4.2.2 Interest Operators: In the selection of points of interest, which represent the surface being measured, point density must be balanced against the high demand on computational time during the image matching process. The number of selected points must be sufficient to accurately represent the surface while avoiding unnecessary point density leading to unacceptable computational times. Original tests showed that unwanted point accumulations can occur in local areas as a result of unsuitable interest operators. In order to optimise this process three interest operators were investigated.

Firstly, the **Canny Interest Operator** (Canny, 1986) uses an approximation to the first derivative of the Gaussian function to generate a convolution kernel. The Canny kernel is convolved in both x and y-directions in the image. Due to the nature of the Gaussian function, the Canny operator has a smoothing effect that tends to eliminate noise and low magnitude edges in the image.

Secondly, the **Sobel Interest Operator** (Haralick, 1992) is of similar form to the Canny operator, but does not provide any smoothing. The Sobel filter is unidirectional in two dimensions and is convolved in both image directions.

Lastly, the method of determination of the **Maximum Gradient** (van der Vlugt, 1994) makes use of the neighbouring pixels surrounding the pixel of interest to locate the magnitude and direction of the maximum gradient (edge vector) at the pixel of interest. Figure 2 gives a diagrammatic description of the algorithm used for the method of maximum gradient location.

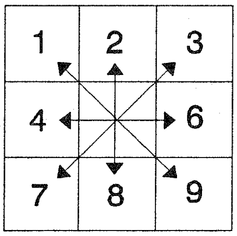

Figure 2 - Maximum Gradient Filter

$$gradient = \frac{(g_i - g_j)}{dist(i,j)} \quad where \quad i=1\rightarrow4,\ j=9\rightarrow6 \qquad (1)$$

The edge information derived from the convolution of the images with the operators provides edge strength for all three cases, where an user-selected threshold value rejects weak edge points. For the Canny and Sobel operators, edge directions are found by forming gradient vectors from the x and y convolution values for each selected edge point, while the maximum gradient operator directly provides edge directions to the nearest 45 degrees. Selected edge points form the centre of resampled linear pixel arrays for subpixel edge detection based on the **preservation of moments** method (Mikhail, 1984).

The results of the application of the three edge operators to the rock surface images did not make it possible to conclusively select one as most suitable for the surface texture of the stope face. Local variations in the structure of the surface responded differently to the three operators and no systematic behaviour could be established. It was therefore decided to apply all three operators to each of the images and to rely on inspection and point count to select the best resulting point cloud.

4.3 Image Matching

Once the points of interest have been detected in the "target" image, they need to be "matched" with corresponding points in the "search" (conjugate) images in order to calculate their object space co-ordinates. This is the most computationally extensive and complex of digital photogrammetric tasks and warrants closer investigation.

Image matching has been approached in two distinct but interlinked processes. Epipolar geometry supplies estimates to the initial image co-ordinates of the corresponding points in the conjugate images (Wong, 1986). This is followed up be least squares, grey-scale matching (Gruen, 1988) to determine the final matching image positions.

4.3.1 Epipolar Geometry: In order to find the corresponding points in conjugate images with no *a-priori* knowledge of the search patch positions, epipolar geometry is used to initialise the search. Figure 3 below shows the basic principle of epipolar geometry as a tool in image matching.

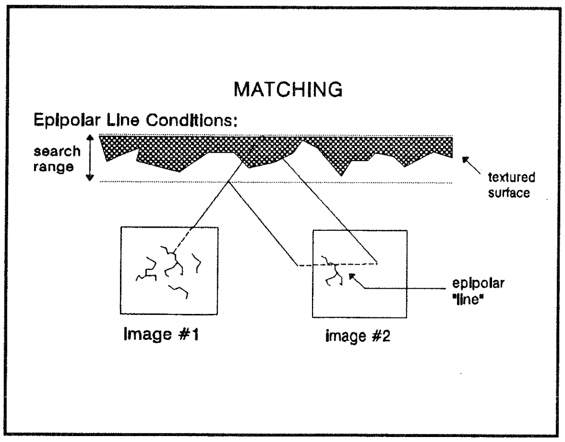

Figure 3 - Epipolar Matching

From projective geometry for the "target" image, the following relationship exists:

$$x = x_p - dx + c\,\frac{r_{11}(X-X_c)+r_{12}(Y-Y_c)+r_{13}(Z-Z_c)}{r_{31}(X-X_c)+r_{32}(Y-Y_c)+r_{33}(Z-Z_c)} \qquad (2)$$

$$y = y_p - dy + c\,\frac{r_{21}(X-X_c)+r_{22}(Y-Y_c)+r_{23}(Z-Z_c)}{r_{31}(X-X_c)+r_{32}(Y-Y_c)+r_{33}(Z-Z_c)} \qquad (3)$$

where x, y are image co-ordinates of the point of interest in the "target" image; x_p,y_p and c are the principal point position and principal distance of the camera, as calculated in pre-calibration; dx, dy are the lens distortion parameters as defined in (4) and (5) below; X, Y, Z are the object space co-ordinates of the point of interest; X_c, Y_c, Z_c are the perspective centre co-ordinates of the "target" image and r_{11}...r_{33} are the rotation matrix elements derived from the camera orientation angles.

$$\begin{aligned} dx &= \bar{x}S_x + \bar{y}a + \bar{x}(K_1r^2+K_2r^4+K_3r^6)+ \\ &+P_1(r^2+2\bar{x}^2)+2P_2\bar{x}\bar{y} \end{aligned} \qquad (4)$$

$$dy = \bar{x}a + \bar{y}(K_1r^2+K_2r^4+K_3r^6)+2P_1\bar{x}\bar{y}+P_2(r^2+2\bar{y}^2) \qquad (5)$$

where S_x is the scale factor in the x-direction and *a* is a shearing factor allowing for affine deformations. K_1,K_2,K_3 are radial lens distortion parameters and P_1,P_2 are decentring distortion parameters,

$$\begin{aligned} \bar{x} &= x-x_p \\ \bar{y} &= y-y_p \\ r &= \sqrt{\bar{x}^2+\bar{y}^2} \end{aligned} \qquad (6)$$

Pre-selecting Z values at regular intervals within the constraint of the epipolar line makes it possible to evaluate a series of X and Y object space co-ordinates of potential candidates, corresponding to the points of interest. The point interval is chosen to a step of 1 pixel in image space. The search range along the epipolar line can be limited with prior estimation of the object depth.

The X/Y co-ordinates are evaluated from the collinearity equations (2) and (3) in the form:

$$\begin{bmatrix} \Delta Xr_{31}-cr_{11} & \Delta Xr_{32}-cr_{12} \\ \Delta Yr_{31}-cr_{21} & \Delta Yr_{32}-cr_{22} \end{bmatrix} \begin{bmatrix} X \\ Y \end{bmatrix} = \begin{bmatrix} RHS_1 \\ RHS_2 \end{bmatrix} \qquad (7)$$

hence

$$\begin{bmatrix} X \\ Y \end{bmatrix} = \begin{bmatrix} \Delta Xr_{31}-cr_{11} & \Delta Xr_{32}-cr_{12} \\ \Delta Yr_{31}-cr_{21} & \Delta Yr_{32}-cr_{22} \end{bmatrix}^{-1} \begin{bmatrix} RHS_1 \\ RHS_2 \end{bmatrix} \qquad (8)$$

where

$$\begin{aligned} \Delta X &= x-x_p+dx \\ \Delta Y &= y-y_p+dy \end{aligned} \qquad (9)$$

and

$$\begin{aligned} RHS_1 = &-(\Delta Xr_{33}-cr_{13})Z+(\Delta Xr_{31}-cr_{11})X_c+ \\ &+(\Delta Xr_{32}-cr_{12})Y_c+(\Delta Xr_{33}-cr_{13})Z_c \end{aligned} \qquad (10)$$

$$\begin{aligned} RHS_2 = &-(\Delta Yr_{33}-cr_{23})Z+(\Delta Yr_{31}-cr_{21})X_c+ \\ &+(\Delta Yr_{32}-cr_{22})Y_c+(\Delta Yr_{33}-cr_{23})Z_c \end{aligned} \qquad (11)$$

In the next step, the image co-ordinates of the candidates in the conjugate "search" images are calculated using the collinearity equations (2) and (3).

A window surrounding the image position of each of the candidates along the epipolar line is used to determine the correlation (R_{XY}) between the "target" image patch and the respective "search" image patches.

$$R_{XY} = \frac{\Sigma\ (g_t-\bar{g}_t)(g_s-\bar{g}_s)}{\sqrt{\Sigma\ (g_t-\bar{g}_t)^2}\sqrt{\Sigma\ (g_s-\bar{g}_s)^2}} \qquad (12)$$

where g_t and g_s represent the grey-scale values on the "target" and "search" windows respectively and g_t and g_s the average grey-scale values for the "target" and "search" windows respectively.

This process is executed for the full extent of the search depth range and the maximum correlation, i.e. the value closest to 1, is chosen as corresponding to the most likely match for the point of interest in the search images. This position is then refined in a least squares, grey-scale area-based matching algorithm with imposed geometric constraints.

4.3.2 Least Squares Matching with Geometric Constraints: The area based process employed for the refined matching of the point position relies on the correlation of grey-scale patches in target and conjugate search images. The initial estimate of corresponding pixels in conjugate images, as provided by the epipolar matching, is required to within one or two pixels (the "pull-in range") in order to achieve a solution. In order to obtain an optimum accuracy for the final point position, the area-based least squares algorithm is supported by affine patch shaping and geometric constraints in the form of the collinearity equations (Gruen, 1988).

4.4 Space Intersection

In addition to providing geometric constraints to the least squares matching, the collinearity equations also serve to produce the three dimensional (XYZ) object space co-ordinates of the points of interest, which are being matched after selection of the best candidate. The image matching routine produces both digital elevation model (DEM) data in the form of XYZ co-ordinates and error estimates for the object space co-ordinates as a consequence of the least squares estimation model.

During the tests carried out for the project the desired sub-millimetre accuracy was achieved for all points in depth, while X and Y ordinates proved typically better by approximately a factor of ten.

4.5 Deformation Analysis

The output of the digital photogrammetric process is a dense point cloud of three dimensional (XYZ) co-ordinates which represent the rock face. This data is processed further in finite element models for rock mechanics studies of the blasting process during pre-conditioning. Results of this aspect of the project will be reported elsewhere.

5. CONCLUDING REMARKS

The final analysis of the data made it apparent that digital photogrammetry is highly suitable for the determination of rock surface digital elevation models for subsequent deformations analysis. The relative speed of the process and the convenient size of the equipment made the technology especially suited to the demanding underground mining environment. Difficulties which arose from the size, shape and environment of the object in the highly restrictive environment, were overcome by careful planning and pre-analysis which led to the incorporation of additional tie points placed on target poles in front of the object. The feasibility of this approach was confirmed by the high accuracy of the final surface point co-ordinates.

For future application of the technique, a second reference frame at the opposite extreme of the wall is proposed. The digital form of the images also makes it possible to employ image processing techniques for fracture pattern analysis and particle analysis.

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