

정밀 화상계측법을 이용한 암반변위 계측시스템

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Rock Displacement Measurement System by Precise Vision Metrology

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Abstract For the purpose of evaluating the safety of rock structures such as underground caverns, tunnels and slopes, rock displacement measurement is carried out to identify the behavior of rock masses. Tapes, levels, and total stations are usually applied to the displacement measurement. These tools, however, are weighed down by many disadvantages. In this study, a new displacement measurement system by precise vision metrology was proposed for the observational design and construction method of rock structures, and then applied to a tunnel under construction. Comparisons and investigations of the measurement of the tunnel have confirmed the effectiveness and applicability of the developed measurement system.

Key words Rock displacement measurement system, Precise vision metrology, Observational design and construction method, Rock structure

초 록 지하공간, 터널, 사면 등 암반구조물의 안정성 평가하기 위해서 필요한 것은 암반변위의 계측이다. 암반구조물의 계측은 아직도 줄자, 레벨 또는 토탈스테이션 등을 이용하는 계측 방법에 의존하고 있는 것이 일반적인 실정이다. 하지만 이러한 방법들은 많은 결점들을 가지고 있어 새로운 방법의 모색이 필요하다. 본 연구에서는 암반구조물에서의 정보화 설계시공의 계측기법으로 개발한 정밀 화상계측법을 이용한 암반변위 계측시스템을 제안하고, 건설 중에 있는 터널에 적용했다. 실제 건설 중에 있는 터널현장에 적용하여 계측결과를 비교 검토함으로써, 개발한 정밀 화상계측법을 이용한 암반변위 계측시스템의 유효성과 적용성에 대한 검증을 하였다.

핵심어 암반변위 계측시스템, 정밀 화상계측법, 정보화 설계시공, 암반구조물

1. INTRODUCTION

For the purpose of the evaluation of the safety of rock structures, displacement measurements should be carried out to identify the behavior of rock structures. The deformational properties of a rock mass are important factors of the safe design and construction of rock structures. Measurement is an essential element of the observational design and construction method of rock structures (Ohnishi, 1999, Hwang, 2003, Hwang et al., 2004). Measurement can help determining the

discontinuity characteristics, the behavior of rock mass, the depth of the loosened zone, in-situ modulus, and other items that should be considered in design of rock structure.

In the case of tunnel design, convergence measurement and electro-optical distance measuring instruments are usually used for inner displacement surveys and crown settlement surveys. But these two methods have weaknesses. The one costs much to undertake survey operation and needs the setting of bolts in advance, while the other needs expensive machines and is also not easy to move. There is, in addition, one more significant inherent defect in them which cannot be denied. In the case of the measurements of many points, they do not work successfully. Because of these disadvantages of the conventional methods,

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a new and improved method was required to be developed. The measurement here means a survey of rock displacement.

In this study, a new rock displacement measurement system by precise vision metrology is proposed for the observational design and construction method of rock structures, and then applied to a tunnel under construction. With a developed self-calibrating bundle adjustment method, the interior orientation parameters of camera and lens distortion are determined at the same time when object coordinates are calculated. Higher measurement accuracy of 3D object coordinate can be obtained by the self-calibrating bundle adjustment method.

2. PRINCIPLES OF PRECISE VISION METROLOGY

Precise vision metrology is a 3-D coordinate measurement technology that is based on the principle of photogrammetry. By taking images from at least two different locations and measuring the points of interest in each image, one can develop lines of sight from each camera location to the points of interest on the object. The intersection of these pairs of lines of sight can then be triangulated to produce the 3-D coordinates of the point on the object. In this way, a pair of 2-D measurements of x , y positions of a point in each photograph which is projected on a 2-D plane are used to produce the measurement of the unique X , Y , and Z coordinates for the point on the object. There

are two kinds of photogrammetry. One is stereo photogrammetry and the other is convergent photogrammetry. With the stereo photogrammetry, the operator is essentially mimicking the operation of human eyes' movement in providing depth perception.

Here, two photographs are taken with the camera axes being parallel (Fig. 1 (a)), and then the photographs are placed in a specialized instrument called a stereo comparator. After an orientation process, the operator can view the two photographs stereoscopically, and see the object as a 3-D model. Because the operator guides the measuring mark to whichever measurement is desired, stereo photogrammetry can eliminate the need for targeting as required by convergent photogrammetry. Unfortunately, stereo photogrammetry, although quite appealing in theory, is difficult to use in practice in many industrial applications because of the labor-intensive nature of the measuring process, and the high degree of operator skill requirement. Also, stereo measurement is less accurate than convergent measurement for several reasons (e.g. low accuracy in the x -direction, y -direction, z -direction, and the limitations of using just two photographs). As a result, stereo photogrammetry is not widely used in industrial applications. The convergent process does not attempt to use the stereoscopic observation capabilities of human vision system to make measurement. Instead, photographs are taken with the camera axes typically inclined towards each other so that the camera axes converge or intersect (Fig. 1 (b)). One now measures easily identified features in each

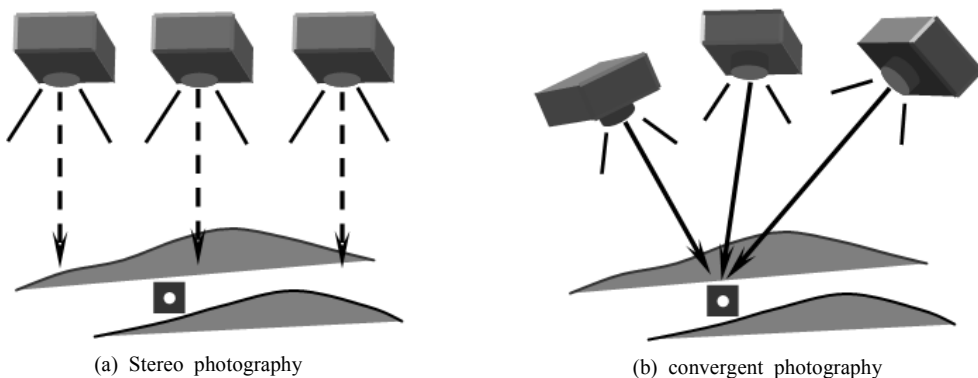


Fig. 1. Stereo photography and convergent photography

photograph, and these two measurements are combined together to produce the 3-D coordinates of the points. In order to achieve a high degree of reliability, accuracy and automation (of the detection and identification of targets) in the measuring process, one normally measures high-contrast targets placed on or near the points of interest on the object (e.g. tunnel, slope, structure, etc.). Most convergent measurement today is using targets. Unlike the stereo method, the convergent measurement is not limited to using just two photographs of an object at a time. The method can be taken many photographs if desired on one occasion; this leads to higher accuracy and reliability and makes it much easier to measure complex objects which cannot be completely seen in just two photographs.

The precise vision metrology system studied herein uses convergent photography.

3. ADVANTAGES OF PRECISE VISION METROLOGY

Vision metrology is now being used in Japan, Europe, and the United States, etc. to measure the configuration of comparatively large objects such as rockets, ships and automobiles. It has been reported that vision metrology systems have delivered accuracies generally about 1:50000 of the principal dimension of the object. Thanks to the appearance of high resolution digital cameras and high speed personal computers with large capacity, it has become relatively simple and inexpensive to use. The comparison among the different methods used for rock measurement is summarized in Table 1.

Important points in any discussion of advantages of a measuring technique are the measurement accuracy and reliability. Calculating the reliability of the measurement process is central to any consideration of accuracy. In this regard, vision metrology displays considerable advantages over the theodolite system. The high degree of data redundancy from multi-ray triangulation gives it a high statistical reliability. Moreover, in a more general reliability context the image constitutes a permanent record of the observational data. This is a crucial consideration for quality inspection programs since it provides a degree of traceability in that coordinate data can be re-measured as required. The second major advantage of industrial vision metrology is its productivity. Two important factors are the speed of data acquisition and automated measurement of photography. In an application of digital theodolite systems to the inspection of large assembly machine when it is running, the machine must be taken out of production for an extended period of time. By use of vision metrology, on the other hand, minimal breakdown is involved since photography can take place typically in few minutes for a simple object and a few tens of minutes for one which is of moderate complexity. While it is true that vision metrology cannot provide instant 3-D coordinate data, such a requirement is generally of limited consequence in inspection surveys. What is important is that the measurement process should cause minimum disruption to production. The time and operator skill level requirements of manual film reading impede the progress of vision metrology and its application to the industrial measurements. With an automated image

Table 1. Comparison among the methods used for rock measurement (Hwang, 2003)

	Cost	Applicability	Convenience	Accuracy
Convergence measure	×	×	×	○
Electro-optical distance measuring instruments	×	○	×	×
Borehole displacement meter	×	×	×	○
GPS	×	×	○	○
Fiber optics technique	×	○	○	△
MONMOS	×	×	×	○
Precise vision metrology	○	○	○	○

measurement this bottleneck has been removed. Automation substantially improves both productivity and accuracy, thus presenting a far more economical and acceptable approach to the vision metrological measurement.

The precise vision metrology is a new and attractive technique in the surveying of rock engineering structures. Because the position information of many points is included in one image, area measurements can be made easily. With the measurement of the 3-D elements of an object and their displacements, the shape change of object can be determined. Displacement survey with vision metrology can be implemented remotely. The method can be used in field surveys at the locations such as a dam or a cliff, where the surveyor can not approach. Real time survey can be realized because the whole survey procedures from photography to data reduction takes just a few minutes. This leads to the minimization and even elimination of any interruption to the construction process. The faster feedback allows to check construction quality in time and to revise original design when necessary. The survey system is quite simple because one CCD (Charge Coupled Device) camera and one PC are enough for the measurement, and photography is very easy to complete. The simplicity decreases measurement costs to a very low level.

4. ROCK DISPLACEMENT MEASUREMENT SYSTEM

In order to measure by precise vision metrology, a measurement system applying principle of precise vision metrology is essential. Some basic hardwares including camera, target, scale, PC and softwares likes image processing software, pre-process software for precise adjustment, and precise adjustment software are required in a measurement procedure in which measurement works of determining the size, shape and movement of objects are implemented as a consequence of analyzing images recorded on film or electronic media. Based on the basic principles of vision metrology described above, a new measurement system by precise vision metrology is developed. The basic requirements of the system for processing the digital data will

differ according to the application. The requirements for topographic mapping are based on the need for recording continuous features and for being able to view a complete overlap of a pair of aerial photographs. For close range work, point measurement on smaller images is more common.

A vision metrological system used for close range work has to satisfy the following requirements: capability for self-diagnosis, potential for high precision and reliability, and task flexibility with respect to 3-D object reconstruction functions. A measurement system should not depend solely on the operator's experience and good judgment, but also should be supported by a more objective statistical evaluation of results. Precision describes the statistical variability of the parameters estimated in the adjustment process. Reliability is the ability to detect the influence of measurement errors. Both the precision and reliability can be improved by high degree of data redundancy provided by multi-ray triangulation (Fig. 2). A vision metrological system is a reconstruction process of 3-D object space. The measurement system by vision metrology should be flexible enough to be applied to different measurement tasks. In any vision metrological process, there are two major phases: ① acquiring data from the object to be measured by taking the necessary images and ② transforming the images into maps or spatial coordinates, this is, converting the images into analog or digital data. Thus, the total vision metrology system can be subdivided into two major divisions, data acquisition and data transformation. The data acquisition system is concerned with procuring what may be termed the raw data or raw information. The raw data are realized in terms of the image. Hence

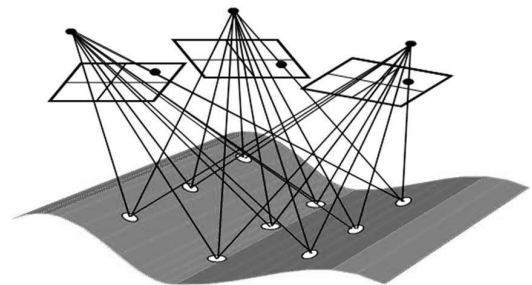


Fig. 2. Multi-ray triangulation.

the data acquisition system is concerned with obtaining necessary and suitable photography (Atkinson, 1980). The data reduction system is concerned with converting the raw data or images into a final data form suitable for the intended use of those data. The final data form may be analog, such as a map, or digital, such as spatial coordinates. The measurement system used in this study consists of the following steps:

- i) Optimization design of photographing network
- ii) Targeting
- iii) Photography
- iv) Accurate 2-D coordinate measurement of targets
- v) Data reduction of 3-D coordinates of targets
- vi) Output of displacement result.

Some basic hardware and software must be provided during these procedures. Fig. 3 illustrates the basic measurement system by precise vision metrology.

Regardless of the nature of the computer vision metrological measurement task, a common goal should be the maximization of overall quality within the constraints imposed by these requirements and specifications varied greatly from application to application. In optimizing the measurement operation, usually in terms of accuracy and economy, particular attention must be paid to the quality of the photographing network design. Design quality can in turn be expressed through a number of goal functions, including precision, reliability, economy, and diagnosis ability. Of the goal functions mentioned, precision is determined at the design stage through the choice of an observation scheme for the network, that is, through the network's geometric configuration. The interrelated reliability

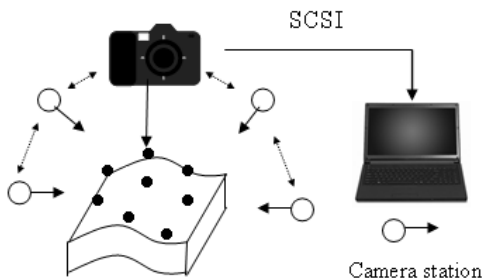


Fig. 3. Measurement system by precise vision metrology.

problem is involved in the ability to find out the influence of measurement errors, that is, with the degree to which the network is self-checking. The process of network design optimization can be carried out through computer simulation. And experience and intuition will play a substantial role in network optimization. The process of computer vision metrology network design optimization is carried out through computer simulation. It facilitates design optimization through the generation of trial vision metrological data sets, for which error propagation is computed and network precision is determined via the self-calibrating bundle adjustment.

Normally measurements are desired between discrete points or a 3-D coordinate is desired in relevance to one or more additional points. The connection between 2-D image coordinates and 3-D object coordinates of an object point can be expressed as,

$$\begin{bmatrix} x \\ y \end{bmatrix} = f(X, Y, Z, X_0, Y_0, Z_0, \omega, \varphi, \kappa, \Delta x, \Delta y) \quad (1)$$

where

(x, y) : 2-D image coordinates

(X, Y, Z) : 3-D object coordinates

(X_0, Y_0, Z_0) : Position coordinates of the camera

$(\omega, \varphi, \kappa)$: Orientations of the camera

$(\Delta x, \Delta y)$: Factors of internal geometric and optical characteristics of the camera.

The targets should be high retro-reflective and light in weight so the target can stick easily to a rock surface. The used targets are made of a thin, greyish-colored self-adhesive retro-reflective material. The targets are normally illuminated by a small, battery-powered strobe located at the camera. The use of retro-reflective material greatly simplifies photography. The strobe makes exposure of the targets independent of the ambient light level. This means the object can be photographed in bright light or total darkness, and the target exposure will be the same. Furthermore, the strobe power is low enough that the strobe does not illuminate the object. Thus, the target and object exposures are largely independent, with target exposure provided by the strobe, and object exposure provided

by the ambient light. By setting the shutter exposure time appropriately, one can expose the object to whatever level desired. Although one can make a normal exposure, usually the object is significantly underexposed to make the target measurement easier and more reliable. Retro-reflective targets also make measuring images easy. With the background underexposed, only the targets show up on the image. This greatly simplifies the measuring process and allows fast, reliable and automated target measuring algorithms to be used. Since the operator is only involved in guiding the process along and not in the actual measuring of the target centroid, measuring accuracy and operator skill are independent of each other. Finally, because the targets are illuminated by a very high-speed flash, possible camera instability is out of the question. This means the camera can be used in vibrating environments or on unstable platforms such as cranes, manlifts, and so forth, if necessary. This ability to work in unstable environments is an extremely attractive advantage of vision metrology over other high-accuracy, portable measuring methods which must be stable throughout the measurement.

A camera is the only measurement device needed for field survey. The ways with which cameras are used, depending on the application, can be hand held, tripod mounted or be supported by specialized structures. Normally for static measurements, a single camera is moved to each camera station in succession. This requires that the object under inspection be stable. If the subject of the survey is a study of dynamics, high-speed cameras can be used in synchronization, with each set of simultaneous frames providing discrete measurements. Once inputted to a PC, image processing software is used for data transference and image generation.

One of the fundamental steps in vision metrology survey is the detection and identification of targets appearing on a set of photographic images and accurate image coordinate determination. Image processing has improved with advances in microcomputers and the introduction of digital image processing. Infinite repetitive quantitative measurement is successfully accomplished through automatic systems. With the introduction of digital image processing, measurement

points on images can be recognized easily by computer algorithms. The detection and identification of targets can be implemented by two step semi-automatic processing system so far. First, some 4-6 points in each image are identified manually and an approximate orientation is accomplished by bundle adjustment using these 4-6 points. Then each point that has to be measured in at least two images is identified manually. The rest of the points can thereafter be detected via epipolar line intersection.

The complete automatic detection of signaled targets is now on the way of research. The accuracy of image coordinate determination is a main factor in overall system accuracy (Fig. 4). Vision metrology requires that the accuracy of image coordinate measurement be 1 and 0.2 micron. A number of techniques exist for the automatic determination of the image coordinates of targets, like template matching, ellipse operators, centroid operators, or other area-based or edge-based techniques in all of which the coordinate of target centroid is measured automatically. The selection of a suitable technique depends on the size of targets, the contract situation at the object and illumination influences. By these operators the accuracy of 1/20... 1/50 pixel in image space can be usually achieved (Maas, 1994), which is by far better than 'manual' measurement on the screen.

Self-calibrating bundle adjustment with a number of advantages is used for data reduction of 3-D coordinates of targets. The general collinearity equations can be written in the form:

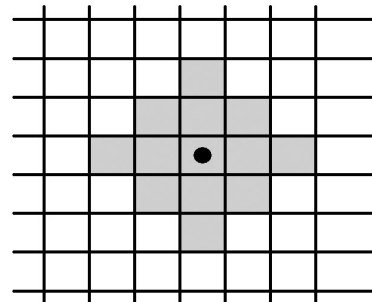


Fig. 4. 2-D Coordinate measurement of targets.

$$\begin{aligned} x_c &= x_H + \Delta x - c \frac{a_{11}(X - X_0) + a_{12}(Y - Y_0) + a_{13}(Z - Z_0)}{a_{31}(X - X_0) + a_{32}(Y - Y_0) + a_{33}(Z - Z_0)} \\ y_c &= y_H + \Delta y - c \frac{a_{21}(X - X_0) + a_{22}(Y - Y_0) + a_{23}(Z - Z_0)}{a_{31}(X - X_0) + a_{32}(Y - Y_0) + a_{33}(Z - Z_0)} \end{aligned} \quad (2)$$

where the image coordinates of object point constitute observations.

There are 3 groups of unknowns named 3-D coordinates of object points (X, Y, Z), interior orientation parameters including focal length c , principal point offsets of image and perturbation terms accounting for departures from collinearity due to lens and image distortion, and exterior orientation parameters consisting of sensor position, and orientation of each image which constitutes a rotation matrix (Eq. (3)).

$$\begin{aligned} \begin{bmatrix} a_{11}^i & a_{12}^i & a_{13}^i \\ a_{21}^i & a_{22}^i & a_{23}^i \\ a_{31}^i & a_{32}^i & a_{33}^i \end{bmatrix} &= \begin{bmatrix} \cos \kappa_i & \sin \kappa_i & 0 \\ -\sin \kappa_i & \cos \kappa_i & 0 \\ 0 & 0 & 1 \end{bmatrix} \\ \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \omega_i & \sin \omega_i \\ 0 & -\sin \omega_i & \cos \omega_i \end{bmatrix} &\begin{bmatrix} \cos \varphi_i & 0 & -\sin \varphi_i \\ 0 & 1 & 0 \\ \sin \varphi_i & 0 & \cos \varphi_i \end{bmatrix} \end{aligned} \quad (3)$$

Eq. (2) is a non-linear function of unknowns of orientation parameters and coordinates of object point. Its linear form can be written as

$$L = A\Delta x \quad (4)$$

$$L = \begin{bmatrix} x_c - \bar{x}_c \\ y_c - \bar{y}_c \end{bmatrix} \quad (5)$$

$$A = \begin{bmatrix} \frac{\partial x_c}{\partial op_i} & \frac{\partial x_c}{\partial op_e} & \frac{\partial x_c}{\partial ld} & \frac{\partial x_c}{\partial oc} \\ \frac{\partial y_c}{\partial op_i} & \frac{\partial y_c}{\partial op_e} & \frac{\partial y_c}{\partial ld} & \frac{\partial y_c}{\partial oc} \end{bmatrix} \quad (6)$$

$$\Delta x = [\Delta op_i \quad \Delta op_e \quad \Delta ld \quad \Delta oc]^T \quad (7)$$

op_i : interior orientation parameters; $op_i = (x_H \quad y_H \quad c)$

ld : lens distortion; $ld = (k_1 \quad k_2 \quad k_3 \quad p_1 \quad p_2)$

op_e : exterior orientation parameters;

$$op_e = (X_0 \quad Y_0 \quad Z_0 \quad \varphi \quad \omega \quad \kappa)$$

oc : object coordinates; $oc = (X \quad Y \quad Z)$.

By use of Least Squares Estimation, the corrections Δx to approximations x_0 of unknowns can be obtained based on the weighted least squares criterion $V^T P V \rightarrow \min$. Here V is a residual vector of the measurements. In iterative calculation, the result of the first cycle is taken as approximation of the second cycle and so on until the correction vector is enough small as can be negligible (Eq. (8)).

$$x^{(i)} = x^{(i-1)} + \Delta x^{(i)} \quad (8)$$

In bundle adjustment method, all orientation parameters and space coordinates of points are determined simultaneously. The general collinearity equations are adopted directly as the determination equations. The adjustment procedure will be described in following sections.

To take metric camera as example, orientation parameters are $(\omega_1, \varphi_1, \kappa_1, X_{01}, Y_{01}, Z_{01})$ for left photograph and $(\omega_2, \varphi_2, \kappa_2, X_{02}, Y_{02}, Z_{02})$ for right one. The general collinearity equations are written down together for a stereo pair of pictures in the form:

$$\begin{aligned} x_i &= -c_i \frac{a_{11}^i(X - X_{0i}) + a_{12}^i(Y - Y_{0i}) + a_{13}^i(Z - Z_{0i})}{a_{31}^i(X - X_{0i}) + a_{32}^i(Y - Y_{0i}) + a_{33}^i(Z - Z_{0i})} \\ y_i &= -c_i \frac{a_{21}^i(X - X_{0i}) + a_{22}^i(Y - Y_{0i}) + a_{23}^i(Z - Z_{0i})}{a_{31}^i(X - X_{0i}) + a_{32}^i(Y - Y_{0i}) + a_{33}^i(Z - Z_{0i})} \end{aligned} \quad (9)$$

where

$$\begin{aligned} \begin{bmatrix} a_{11}^i & a_{12}^i & a_{13}^i \\ a_{21}^i & a_{22}^i & a_{23}^i \\ a_{31}^i & a_{32}^i & a_{33}^i \end{bmatrix} &= \begin{bmatrix} \cos \kappa_i & \sin \kappa_i & 0 \\ -\sin \kappa_i & \cos \kappa_i & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \omega_i & \sin \omega_i \\ 0 & -\sin \omega_i & \cos \omega_i \end{bmatrix} \begin{bmatrix} \cos \varphi_i & 0 & -\sin \varphi_i \\ 0 & 1 & 0 \\ \sin \varphi_i & 0 & \cos \varphi_i \end{bmatrix} \\ (i=1,2) \end{aligned}$$

Eq. (9) includes mathematically one equation equivalent to the coplanarity condition of corresponding rays. Thus, five coplanarity equations are obtained when Eq. (9) is set up with five object points mathematically required in which only two points and one height are given as control points. Having five object points, total 20 equations are obtained. In 5 object points, 8 unknowns of coordinates of object points exist. So, there are total 20 unknowns.

The necessary orientation parameters can be determined for the unique determination of all photographed object points. In fact, more than two points and one height are used as control points or more than 5 object points are treated by use of least squares method. That all orientation parameters and space coordinates of points are determined simultaneously makes the method to be a simpler and more attractive method.

Bundle adjustment method holds a number of advantages : (a) Higher accuracy. (b) Flexibility resulting from an ability to combine vision metrological and surveying observations simultaneously in the adjustment. (c) Lack of necessity to provide highly redundant object space control especially when free-net solution is incorporated. (d) Modeling of systematic errors such as lens and film distortion without recourse to making specific additional observations for this purpose; self-calibration can be incorporated to form self-calibration bundle solution. (e) Strong agreement between estimates of precision as given by statistical indicators such as root-mean-square errors and accuracy determined with respect to check-point control.

With a developed self-calibrating bundle adjustment method in this study, the interior orientation parameters of camera and lens distortion are introduced in adjustment procedure and determined at the same time when object coordinates are calculated. Higher measurement accuracy of 3D object coordinate can be obtained by the self-calibrating bundle adjustment method.

5. DISPLACEMENT MEASUREMENT WITHIN AN ACTUAL TUNNEL

5.1 Network Geometry

The actual example site selected in this study is the

tunnel under construction that served as an experiment tunnel for the hydraulic power station. This tunnel has a section size of 5 m by 5 m. A total of three “sections” are measured as excavation proceeds. Each “section” has an axial length of 3 meters and the spacing between two neighboring “sections” is 5 meters. These “sections” are measured 5, 4 and 2 times respectively as excavation proceeds. Thus, a total of 11 epochs i.e. 11 times of measurements are made in two months (Table 2).

The anticipated precision of rock displacement measurement is 1 mm. A mean measurement precision of 0.5 mm for target XYZ coordinate is established for each epoch as a one-number accuracy criterion. In this measurement project, the available camera was a Minolta with a color CCD sensor that has 1528×1146 elements. The color sensor will cause a significant degradation to image coordinate mensuration. The image coordinate mensuration precision of $\sigma=2.5 \mu\text{m}$ was assumed in this measurement work by a trial and error method. Based on these factors an imaging scale of 1:200 was designed. When coupled with a 28 mm lens, this means a photography distance of 5.6 meters is needed.

A target array is designed (Fig. 5) based on



Fig. 5. The actual tunnel and the arrangement pattern of targets.

Table 2. Measurement arrangement at the actual tunnel

	1 st Survey	2 nd Survey	3 rd Survey	4 th Survey	5 th Survey	Times of measurement
Section 1	○	○	○	○	○	5
Section 2		○	○	○	○	4
Section 3				○	○	2
Times of measurement	1	2	2	3	3	11

measurement requirement and geometric features of the object to be photographed. A total of 21, 27 and 29 targets were placed on the heads of rock bolts through a metal angle set for the respective sections. For the purpose of compensation of lens and image distortion and provision of further constraints in bundle adjustment, two staffs serving as scale bars were hung at the roof of the tunnel at each measurement epoch. On account of the limit of the measurement circumstances in this tunnel field, it is difficult to use some static points as control points in determination of coordinate system. In this tunnel, the deformation at the upper part of tunnel section is notably larger than that at the lower part, three points near the floor of the tunnel are assumed as control points to determine the object coordinate system. The 3-D coordinates of two points and y coordinate of one point are set arbitrarily. To provide a strong geometric connection for target array to enhance the precision of measurement, some 40 dummy points were set up on staffs. In all, some 60 targets were to be measured at each epoch.

One proper photographing network configuration was designed by interactive search. There were a total of 20 stations and 2 exposures taken at each station.

5.2 Data Gathering, Processing and Analysis

The Minolta flash unit was used for target illumination. The camera is focused at infinity. Sensitivity of ISO 100, aperture setting of F16 and a shutter speed of 1/125 sec were set in the measurement. The setting of exposure is different from that for the indoor test because of darker ambient light. The camera affords the benefit of immediate image preview via a PC with

SCSI (small computer system interface) and the software package. After field photography, all images were measured and self-calibrating bundle adjustment was performed for each epoch.

5.3 Results and Discussions

Table 3 summarizes the results of bundle adjustments for the 11 measurement epochs. For 11 cases the mean value of standard error of image coordinate measurement was 2.69 μm with a maximum of 3.11 μm and minimum of 2.35 μm . The standard error of image coordinate measurement is close to the expected value of 2.5 μm . The precise vision metrology of 11 cases yielded a mean measurement precision of $\bar{\sigma}_c = 0.30$ mm for the object point XYZ coordinates, which is much better than the design specification of 0.5 mm. In the presence of complete functional and stochastic methods, a basic agreement between the estimates of accuracy and precision should be expected, since the former is an unbiased estimate of the latter. This means that an average measurement accuracy of 0.30 mm for object point XYZ coordinates can be achieved. Based on error propagation law, it can be concluded that the measurement accuracy of rock displacement can be as high as 0.60 mm, and is satisfactory enough for specification in rock displacement survey.

On examining the results more closely, however, it is found that the in-situ measurement accuracy, in this work, represented by precision criterion is lower than that for the indoor test. Of the number of possible sources of errors which need to be examined when seeking the accuracy difference between the indoor and in-situ works, two immediate candidates will be

Table 3. Achieved precision in the actual tunnel measurements

		1 st Survey	2 nd Survey	3 rd Survey	4 th Survey	5 th Survey
Section 1	$\hat{\sigma}_0$ (μm)	2.45	2.59	3.11	2.53	2.73
	$\bar{\sigma}_c$ (mm)	0.45	0.25	0.30	0.24	0.26
Section 2	$\hat{\sigma}_0$ (μm)		2.63	2.89	2.76	2.94
	$\bar{\sigma}_c$ (mm)		0.29	0.33	0.33	0.31
Section 3	$\hat{\sigma}_0$ (μm)				2.35	2.60
	$\bar{\sigma}_c$ (mm)				0.29	0.28

briefly considered here. The first significant element is the effect of blasting on targets. For the purpose of measuring rock displacement immediately after excavation, the nearest survey section is only 3 meters from the tunnel face. Blasting deforms the shape of targets and even makes targets move to some degree. The dust from blasting deteriorates the retro-reflective performance of targets, and this further degrades mensuration accuracy of the image. The blasting effect presented a challenging precise vision metrology survey problem, so some protection means must be taken to achieve a good measurement result. The other is the use of the camera with color version in the project. With the special protection from blasting and use of suitable camera such as DCS420, final measurement accuracy can be much improved.

6. CONCLUSIONS

In this study, a newly developed rock displacement measurement system by precise vision metrology is proposed as a measurement method for the observational design and construction method of rock structures, and then applied to a tunnel under construction. The capability, combined with its fast, flexible, reliable and economical attributes, augurs well for popular future use of measurement system by precise vision metrology in rock structures. In the tunnel, a satisfactory measurement result with high precision is obtained.

The measurement precision of rock displacement in the tunnel construction can mostly fulfill the survey specification in rock engineering. The comparisons and investigations with the measurement results in the tunnel construction have confirmed the effectiveness and applicability of this developed rock displacement measurement system by precise vision metrology.

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