Ubiquitous Monitoring by Precise Vision Metrology for Observational Design and Construction Method in Tunnels
(터널의 정보화 설계시공을 위한 정밀 화상계측법을 이용한 유비쿼터스 계측관리)

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1. Introduction

For the purpose of evaluation of the safety of tunnels and underground spaces, monitoring is carried out to catch the behavior of rock engineering structures. The properties of a rock mass are important factors relevant to the design and construction of rock engineering structures (Ohnishi, 1999; Ohnishi, 2002; Hwang and Sato, 2004; Hwang, 2006). Monitoring is a key element for observational design and construction method in tunnels (Hwang, 2003; Hwang et al. 2004). Measurement can help determine the discontinuity characteristics, the behavior of rock mass, the depth of the loosened zone, in-situ modulus, and other items that may be dealt with in design.

In the case of tunnel measurement, convergence measure and electro-optical distance measuring instruments are usually used for inner displacement survey and crown settlement survey respectively. With an electro-optical distance measuring instrument, the machine cost is high and movement of the machine is difficult. With convergence measure, survey operation cost is high and set of bolt in advance is needed. In addition, when measurements of many points are needed, these methods can not be used effectively. The many disadvantages of these methods make it preferable for a new method to appear.

2. Advantages of vision metrology

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

Table 1. Comparison among the methods used for rock measurement

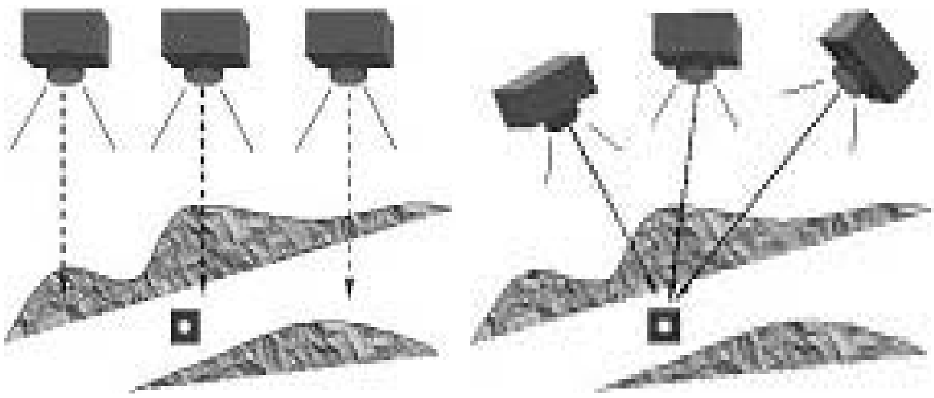
	Cost	Applicability	Convenience	Accuracy
Convergence measure	×	×	×	○
Electro-optical distance measuring instruments	×	○	×	×
GPS	×	×	○	○
Fiber optics technique	×	○	○	△
Digital theodolite	×	×	×	○
Precise vision metrology	○	○	○	○

Perhaps the foremost in any discussion of advantages is measurement accuracy and reliability. 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 an important consideration for quality inspection programs since it provides a degree of traceableness in that coordinate data can be re-measured as required. This is an important consideration for quality control programs since it provides a degree of traceableness in that coordinate data can be re-measured as required. The second major advantage of industrial vision metrology is its productivity. Two factors are of prime importance here, the speed of data acquisition and automated measurement of photography. In applications 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 3D 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 close range vision metrology and its application to industrial measurement. With automated image measurement this bottleneck has been removed. Automation substantially improves both productivity and accuracy, thus presenting a far more economical and acceptable approach to vision metrological measurement.

Vision metrology is a new and attractive technique in the survey of rock engineering structure. Because the position information of many points is included in one image, area measurement can be made easily. 3D element of object is measured, 3D element of displacement is also measured, the shape change of object can thus be obtained. Displacement survey with vision metrology can be implemented remotely. The method can be used in field survey where surveyor can not approach such as a dam or a cliff. Real time survey can be realized because the whole survey procedures from photography to data reduction take a few minutes. This leads to the minimization and even elimination of any interruption to the construction processes. The faster feedback allows checking construction quality in time and revising original design when necessary. The survey system is simple because only one CCD camera and one PC are enough for measurement, and photography is very easy to complete. The simplicity decreases measurement cost to a very low level.

3. Principle of precise vision metrology

Precise vision metrology is 3D 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 3D coordinates of the point on the object. In this way, a pair of 2D measurements of x, y positions of a point in each photograph which is projected on a 2D plane are used to produce the measurement of the unique X, Y, Z coordinates for the point on the object. There are two kinds of photogrammetry. Typically, they are called stereo photogrammetry and convergent photogrammetry. With stereo photogrammetry, operator is essentially mimicking the operations the human eyes perform 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 3D model. Because the operator guides the measuring mark to wherever measurement is desired, stereo photogrammetry eliminates the need of targeting as required by convergent photogrammetry. Unfortunately, stereo photogrammetry, although quite appealing in theory, is hard 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. 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 photograph, and these measurements are combined together to produce the 3D coordinates of the points. To achieve a high degree of reliability, accuracy and automation in the measuring process, one normally measures high-contrast targets placed on or near the points of interest on the object. Most convergent measurement today is done by use of targets. Unlike the stereo method, the convergent method is not limited to using just two photographs of an object at a time. Many photographs can be taken if desired on one occasion; this leads to higher accuracy and reliability and makes it far easier to measure complex objects which can not be completely seen in just two photographs. The vision metrology system studied herein uses convergent photography.



(a) Stereo photography (b) Convergent photography

Fig. 1. Stereo and convergent photography

4. Precise vision metrology measurement system

In order to measure by precise vision metrology, a measurement system applying principle of precise vision metrology is essential. Some basic hardware and 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 principle of vision metrology described above, a developed vision metrology Measurement System is presented in this chapter. The basic requirements of a system for processing digital data will differ according to applications. 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 usual.

A vision metrological system used for close range work has to meet the following requirements: ① capability for self-diagnosis, ② potential for high precision and reliability, and ③ task flexibility with respect to 3D object reconstruction functions. A measurement system should not depend solely on the operator's experience and good judgment, but 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. A vision metrological system is a reconstruction process of 3D 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 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:

(1) Optimization design of photographing network
(2) Targeting
(3) Photography
(4) Accurate 2D coordinate measurement of targets on images
(5) Data reduction of 3D coordinates of targets
(6) Output of displacement result.

Some basic hardware and software must be provided during these procedures. Fig. 2 illustrates the basic computer vision metrology System configuration.

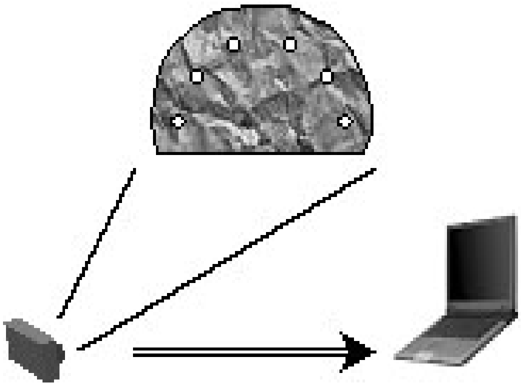


Fig. 2. Precise vision metrology system configuration

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 problem is concerned with the ability to detect 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 an important role in network optimization. The process of computer vision metrology network design optimization is carried out through computer simulation.

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

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

where

(x, y) : 2D image coordinates

(X, Y, Z) : 3D 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 target can be stick easily to rock surface. The targets used 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 is independent of operator skill. Finally, because the targets are illuminated by a very high-speed flash, the 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 the like, if necessary. This ability to work in unstable environments is a major 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 input to the PC, image processing software is used for data transfer 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 been improved with the advances in microcomputers and introduction of digital image processing. Endless repetitive quantitative measurement is best accomplished by 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 performed 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.

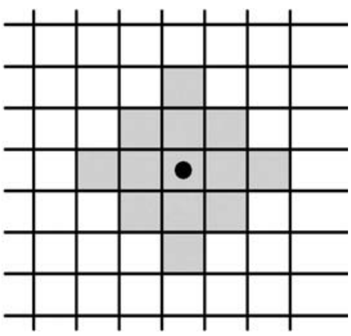


Fig. 3. 2D Coordinate measurement of targets

The complete automatic detection of signalized targets is now on the way of research. The accuracy of image coordinate determination is a central factor in overall system accuracy (Fig. 3). 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 achieved usually (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 3D coordinates of targets. The general collinearity equations can be written in the form:

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

where

the image coordinates x_c, y_c of object point constitute observations.

There are 3 groups of unknowns named 3D coordinates of object points (X,Y,Z), interior orientation parameters including focal length c, principal point offsets x_H, y_H of image and perturbation terms $\Delta x, \Delta y$ accounting for departures from collinearity due to lens and image distortion, and exterior orientation parameters consisting of sensor position (X_0, Y_0, Z_0), and orientation $(\varphi, \omega, \kappa)$ of each image which constitutes a rotation matrix (Eq. (3)).

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

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

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

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

$$A = \begin{bmatrix} \frac{\partial x_c}{\partial op_i} & \frac{\partial x_c}{\partial op_e} & \frac{\partial x_c}{\partial ld} & \frac{\partial x_c}{\partial oc} \\ \frac{\partial y_c}{\partial op_i} & \frac{\partial y_c}{\partial op_e} & \frac{\partial y_c}{\partial ld} & \frac{\partial y_c}{\partial oc} \end{bmatrix}_0 \quad (6)$$

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

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

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

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 Δx is enough small as can be negligible (Eq. (8)).

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

Photo 1. Tunnel model and arrangement pattern of targets

5. Model experiment of precise vision metrology measurement system

One tunnel model with section size 3 m by 3 m consisted of ceiling and 2 walls at a laboratory is taken as a measurement object for a pilot study (Photo 1). The tests of effectiveness of proposed vision metrology system consisting of precise adjustment software and pre-process software of precise adjustment are carried out on the tunnel model at the laboratory. Photography and 3D data reduction were implemented on the model. Movement of micrometers fixed on model walls is surveyed.

Since the final variance of a displacement vector at a point is computed as a function of the summation of the covariance matrices obtained in two times of measurements, one can determine a goal measurement precision of the object point coordinates at each measuring epoch based on error propagation law. Under the assumption that the vision metrology networks will be of the same geometry at the two measuring epochs and measurement precision of point displacements is 1 mm, a goal mean measurement precision $\overline{\sigma}_c$ of XYZ coordinate can be established to be 0.5 mm. Amongst the salient questions that must be addressed regarding the design of the photographing network configuration are the following: What photographic scale is required? What focal length is optimum to balance considerations of field of view and depth of field versus photographic scale? How many camera stations are required? And, in addition to the targets established for purposes of displacement monitoring, will further auxiliary points besides of survey point be required? Turning first to the selection of photographic scale, the following empirical formula can be employed:

$$\overline{\sigma}_c \approx qS\sigma \tag{9}$$

Here, S is the scale number, σ is a global estimate of the standard error of image coordinate measurements, and q is an empirical factor ranging from 0.5 to 0.9 for strong network geometry. As stated above a goal magnitude of the mean measurement precision $\overline{\sigma}_c$ of 3D coordinate was established as being 0.5 mm. When coupled with a image coordinate determination precision of σ=1.0μm and a q value of 0.9, an imaging scale $1/S$ of 1:550 is designed.

In this test work, a 28-mm lens is available. Though no more choices can be made, this lens is well suitable for this survey work. This facility enabled both on-the-job optimization of exposure setting and provided preliminary verification of image mensuration quality. A target array is designed (Photo 1) based on measurement requirement and geometric features of object. There are total 10 targets pasted on micrometers fixed on the model wall of which 4 targets are on the two walls and 6 targets are on the ceiling.

In preparation for lens and image distortion compensation and for further constraints in bundle adjustment, 2 scale bars calibrated by transit were fastened against a wall in both horizontal and vertical positions. Three static points well distributed in target network are designed as control points. Of three control points, two points are fixed on the lift and right wall respectively and one point is fixed on the roof beam near the ceiling. The coordinates of 3 control points are measured by 2 sets of transits with precision of 20″. Based on Fraser (1984), in order to achieve an optimum control configuration, the array of control points is distributed in such way as the centroid of the triangle formed by the three control points is reasonably close to the target array center and the triangle area is maximum. Based on Fraser (1989), the statistical reliability of the vision metrology orientation can be enhanced through the greater redundancy provided by extra targets, and the number and distribution of image points also significantly influences the precision of recovery of sensor calibration parameters in a self-calibration. So, 70 dummy points were set up on the model wall to provide a strong geometric connection. In all, some 90 targets were to be triangulated at two times of measurement, 10 of these were to act as deformation monitoring points and the others as points of vision metrology precision evaluation.

Based on the selection on camera, lens, imaging scale and the designed pattern of target array, a proper network geometry configuration is designed by computer simulation in this study. It facilitates design optimization through the generation of trial vision metrology data sets, for which error propagation is computed and network precision is determined via the self-calibrating bundle adjustment. The design by simulation utilizes coordinates of a representative sample of object points of interest. Then, sequentially, a series of tentative camera stations is examined. Once the camera setup has been established and standard deviations of measured image coordinates are input, the hypothetical image coordinates of object points of interest are computed. Network precision and accuracy are determined via the self-calibrating bundle adjustment. Through the generation of trial data sets, a suitable geometry form of camera station for this measurement task is determined. There are 15 camera stations, 2 exposures at each station are adopted.

Based on imaging geometry that any incident ray subtends an angle of much larger than 25º with the plane surface of the target, planar retro-reflective targets instead of spherical one are employed. The need to keep target sizes to practical dimensions is always a concern in vision metrology especially when large objects and small image scales are involved. Fraser (1995) suggested that minimum minor diameter of five pixels, or 45 μm of circular target for the DCS420 is needed. This would require circular retro targets of 15-mm diameter. Targets with diameter of 15 and 30 mm are used in this study. The arrangement pattern of targets is shown in photo 1. To take all photography in front of the tunnel, targets are fixed by a steel angle.

With DCS420, the user can select between a manual mode and several automatic or semi-automatic exposure programs. For this vision metrology application auto focus was switched off. Retro-reflective targets gave sufficient light and allowed the use of small iris, so that the camera could be permanently focused on infinity. In order to ensure a consistent internal geometry for the camera system throughout the photography, precautions were taken with the lens. The focus barrel was shimmed and taped at the infinity setting to lock it into a stable position. No apparent movement between the lens assembly and the lens mount flange of the camera body was ensured. Although flash of ring-light is often used, a PE-560MG flash was proved to perform well in illuminating the retro-reflective targets. The proper exposure settings for the imaging of retro-reflective targets, which should neither be overexposed nor appear too dark in the digital images, cannot be solved by the automatic exposure programs and require some experience.

Image measuring is initiated by downloading the image into the PC, each image is brought up on the computer screen, measured, and saved. This can be automated to a significant degree using the design data previously obtained or rough XYZ coordinates of at least 4 points surveyed by simple tool such as a type measure in arbitrary reference system. It can also be carried out manually as the operator desires by measuring each point one at a time if needed. After many or all of the images are measured the data is merged together and XYZ coordinates are calculated through a least squares, self-calibrating bundle adjustment software system.

Results of bundle adjustments for the two measurements are summarized in Table 2. The standard error of image coordinate measurements $\hat{\sigma}_0$ is defined by Eq. (10).

$$\hat{\sigma}_0 = \sqrt{\frac{V^T PV}{n-u}} \qquad (10)$$

where

V is residual vector of image coordinates, P is weight vector for observations, n, u are the number of observations and unknowns respectively.

Table 2. Measurement precision and accuracy

Epoch	Camera stations	Residuals of image coordinates measurement (μ m)	Standard error of image coordinate measurements (μ m)	Measurement precision of target coordinates (mm)			Measurement accuracy of displacement (mm)
		V	$\hat{\sigma}_0$	$\bar{\sigma}_{XY}$	$\bar{\sigma}_Z$	$\bar{\sigma}_c$	S_d
1	15+4	0.32	0.74	0.08	0.19	0.11	0.30
2	15+12	0.23	0.48	0.03	0.09	0.06	

Measurement precision of target coordinates $\bar{\sigma}_{XY}, \bar{\sigma}_Z, \bar{\sigma}_c$ are computed. Measurement accuracy of displacement S_d is computed. It can be seen that the two networks have small measurement residuals. The standard errors of image coordinate measurements $\hat{\sigma}_0$ are 0.74 and 0.48μm. This level of standard errors of image coordinate is much better than the anticipated one of 1μm. The mean precision of the two networks are 0.11 and 0.06 mm respectively, which are much better than the design specification of 0.5 mm. There are two factors contributed to this improvement, one is the small standard error of image mensuration mentioned above, and the other is the use of increasing number of exposure stations. In the two networks 4 and 12 additional camera stations are used respectively. The precision improvements that accompany the use of an increasing number of camera stations are verified in this study. This improvement is marked in the first few of increase of camera stations, as in this case the precision improvement from 0.5 to 0.11 mm owing to the use of first 4 additional stations is achieved. The further improvement when more camera stations are used is in no notable way, as in the study the increase number of camera stations from 4 to 12 follows the precision improvement only from 0.11 to 0.06mm. This indicated that the over increase of camera stations has little impact on precision of well-designed vision metrology network. It can also be observed that the well-known discrepancy between $\overline{\sigma}_{xy}$ and $\overline{\sigma}_{z}$ usually happened in stereo 'normal' instead of convergent network is illustrated. The reason for this is considered as that though the two networks are basically convergent ones, the ray intersection are limited in horizontal plane because the all images were taken on floor of the laboratory and no station was distributed at different height along vertical direction for practical operation restrictions.

The final triangulation accuracy for 10 displacement points pasted on micrometers is 0.30mm, which was the RMS discrepancy in object displacements between the 'real value' of reading of micrometer movements and the computer vision metrology result. The result is much better than the design specification of 1mm. The small image mensuration error and the use of additional camera stations are again held accountable for this. The other notable result is that the RMS discrepancy value s_c of fixed-point coordinates between two times of measurements is 0.5 mm that is significantly larger in magnitude than the corresponding $\overline{\sigma}_{c}$ estimates. In the presence of complete functional and stochastic methods a basic agreement between the estimates s_c and $\overline{\sigma}_{c}$ should be expected. The reason for this discrepancy is thought to be due to the incomplete modeling of image deformation. One of the significant uncertainties associated with the vision metrology exploitation of CCD arrays remains unflatness of image plane. The departures from planarity are due to unflatness of the physical chip surface or variations in "depth" of the light sensitive surface; the presence of unflatness will give a significant error source that is not generally amenable to compensation via analytical self calibration techniques. To date, a mitigating circumstance has been that CCD cameras used with vision metrology systems have tended to be narrow angled. As CCD arrays get larger and camera fields of view wider, however, chip unflatness is likely to assume greater significance as accuracy limitation factor.

6. Conclusion

In this paper, a new ubiquitous monitoring by vision metrology was proposed as a measurement method for observational design and construction method in tunnels. Then the model experiment of the ubiquitous monitoring by precise vision metrology developed by the author was carried out in the laboratory. Based on measurement result obtained, it can be concluded that there is substantial potential for the exploitation of precise vision metrology in tunnel measurement.

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