Image-Based Spatial Information Systems for Geologic Logging

Hao Li, Xiaomin Jia, Yueqin Niu and Rui Wang
College of Civil Engineering, Hohai University, 1 Xikang Road, Nanjing 210098, China

Abstract. The present geologic logging is still primarily accomplished by the manual sketch and field surveying, this operating type does not adapt to the process of practical productive forces and the fast response of informationization construction on spot. In order to realize the digitalization of collection, processing, management and analysis in engineering geology, the author has researched and used the application method of measuring non-metric camera, it can reduce the request of special equipment and professional skill in image-based geologic logging. Based on the research, the author has studied and developed the image-based spatial information system used in engineering geologic logging, and has constructed technology system of digital logging based on the information system.

Image-based spatial information system for geologic logging is a special information system, which grounds on the theory of photogrammetry, makes good use of the techniques of close-rang photogrammetry, digital image processing and GIS, and is characteristic of the interdisciplinary cross. The main functions of the system including the automatic creation of the stretched image map of logging objects, digital plotting of structure feature, Image-based measurement of the structural plane’s attitude, management and query of logging attribute and graphic data, output of AutoCAD drawing etc, besides, it can offer the image production of geology reconnaissance for engineering construction. Theoretical precision and result of practical application show that, in image-based geologic logging, the mean square error of position of tunnel and well are less than 0.2m, of slope and foundation pit are less than 0.3m. The mean square error of measuring structural plane’s attitude is less than 0.2°, all of these have met the requirement of engineering geologic logging specifications.

The system has accomplished the transformation from manual work to computer-assisted work in engineering geologic logging, and also has generally improved the technical levels and the working efficiency in aspect of data collection, processing, management and application.

This paper elaborates some main points of image-based spatial information system for geologic logging, including the system's structure and function module design, the principle of work and spatial information processing algorithm, method of precision estimation and analysis of application instance, etc.

Keywords: image-based spatial information system, engineering geologic logging, photogrammetry, precision, non-metric image

1. The goal of system development

The engineering geologic logging is the key step for guaranteeing the project quality in such engineering constructions as transportation, hydroelectricity and mine. The results serve in engineering design, structure stability analysis, project reinforcement and so on. At present, manual sketch and field surveying are the main geological logging methods which are greatly influenced by constructing. They have such drawbacks as low geometric precision of logging and the slow speed of information feedback. It is not enough for the integrity and accuracy of logging results. Simultaneously, it is not easy to query and apply the logging results. For workers, the logging work not only makes great intensity of labour and slow speed of working, but also involves a considerable risk sometimes.

The goal of system’s research and development is to develop image-based spatial information system for geological logging, set up technical system of image-based spatial information system, accomplish the transformation from manual work to computer-assisted work and informationization management in slope engineering geologic logging. The system grounds on the theory and method of engineering geology and photogrammetry, takes use of the techniques of close-rang photogrammetry, digital image processing and
GIS, and take non-metric camera as collecting device of field data.

2. The Design of the System

The total design’s goal of image-based spatial information system for geologic logging is processing images of slopes, tunnels and foundation pits which obtained by non-metric camera, distilling essential factors of geologic logging rapidly and accurately. It creates logging drawing and database of engineering geologic logging. Synchronously, the system manages and queries factor of geologic logging effectively, provides the external data interface and the function extended interface.

According to the technical essential factor, the system’s general structure can be divided into 5 levels, including the special database, the image-based data coding and pretreatment, the extraction of the essential factor of logging and the characteristic description, the external function communication interface and the CAD-assisted mapping. The system’s structure and data flow are illustrated in Figure 1.

![Fig 1.the general structure of system and the data flow](image-url)

![Fig 2 structure of function module for tunnel](image-url)

![Fig.3 working mode of the system](image-url)

The basic function module of the system includes data management, image pretreatment, image mosaic, image rectification, digital geologic logging, query and output of the achievement, etc. The system has
accomplished such main functions as the automatic creation of the stretched image map of logging objects, digital plotting of structure line, image-based measurement of attitude of structural plane, management and query of logging attributes and graphic data, output of AutoCAD drawing etc. Compared with the manual logging, it offers the image-based reconnaissance results for engineering construction.

The tunnel system's functional module structure is shown in Figure 2. The slope and foundation pit system is similar to the tunnel system, but increase such functions as the anomalous excavated surface modeling and image logging, as the slope and foundation pit have some anomalous excavated surface that can’t be expressed by one function.

3. The basic principle and method of the system

3.1. Working mode of the system

Fig.3 shows the working mode of the system:

The digital camera measuring is to choose the imaging distortion model, determinate the distortion coefficient and interior orientation elements, thus to make the non-metric digital camera measurable.

The collection of digital image is a process to obtain digital image of excavation surface. Photo instrument for geologic logging which can set the exterior orientation elements is used in tunnel, on the contrary, object space control points are used at slope and foundation pit.

Image pretreatment includes some steps, such as distortion correction of image, image enhancement, single image space resection of the slope image, etc.

The primary content of image rectification is a process of getting stretched image, which projects the original image which has been eliminated the distortion to the object space, and then expands the object image into plan as request.

The main process of image mosaic is combining the single stretched image to whole segment stretched image map.

The geologic logging system uses the stretched image map as the base map of logging, applying the function of the system to get the results, such as the description of geologic structure, attribute and measurement of attitude.

3.2. Basic algorithm of image rectification of tunnel

The designed excavation surface of tunnel can be seen as some form of cylindrical surface called target-cylindrical. The shape of tunnel usually includes circular, rectangular, gate, horseshoe, etc. Each type of tunnel has its own cylindrical surface, the corresponding basic algorithm of image rectification is different. Next, the circular tunnel the most common and simplest tunnel is taken to explain the principle and methods of image rectification.

The target-cylindrical surface of circular tunnel is cylindrical surface. Fig.4 shows the relationship between circular tunnel and engineering coordinate system. Taking R as the radius of tunnel, the formula for target-cylindrical is:

\[ Y^2 + Z^2 - 2 R Z = 0 \]  \hspace{1cm} (1)

![Fig.4 circular tunnel and its engineering coordinate system](image)

The coordinate of perspective center is \((X_s, Y_s, Z_s)\) in the object coordinate system and the image point is \((u, v, w)\) in the image space auxiliary coordinate system, the linear equation of projection ray (sa) is:

\[
\frac{X - X_s}{u} = \frac{Y - Y_s}{v} = \frac{Z - Z_s}{w} = \lambda
\]  \hspace{1cm} (2)
Where, \([u \ v \ w]'=R[x \ f \ z]'\), \(R\) is the rotation matrix of image. Obviously, the object coordinate \((X, Y, Z)\) of object point(A) can be calculated from (1) and (2).

Actually, the process of projection is complex when considering the tunnel type and the inclined situation of tunnel. Even the same tunnel may have different function with different part of the surface. Angle elements of each image also have their own domain. So before projection, the target-cylindrical surface function corresponding to the pixel should be chosen, and the angle elements of the image in the object coordinate system should be determined.

After projected the original image to the object pixel by pixel and given gray or color to the corresponding pixel, target-cylindrical image will be formed. Taking the circular tunnel for example, the length of the arc is extended from the origin of the coordinate system towards \(Yc\)-axis directions. Taking \((Xc, Yc)\) as the image coordinate of stretched image map’s pixel, as fig 4 shows, they are given by:

\[
\begin{align*}
X_c &= X \\
Y_c &= \begin{cases} 
R \tan^{-1}(Y/(R-Z)) & Y > 0 \text{ and } Z-R \leq 0 \\
R(\tan^{-1}(Y/(R-Z))+\pi) & Y > 0 \text{ and } Z-R > 0 \\
R(\tan^{-1}(Y/(R-Z))+2\pi) & Y < 0 \text{ and } Z-R \geq 0 \\
R(\tan^{-1}(Y/(R-Z))+\pi) & Y < 0 \text{ and } Z-R < 0
\end{cases}
\end{align*}
\]

According to \(X_c, Y_c\) and gray of pixel, we can resample after projecting the pixel to the stretched image map.

### 3.3. Basic algorithm of image rectification of slope and foundation pit

Compared with tunnel, the surfaces of slope and foundation pit are simpler. Most of the surfaces are planes or they can be taken as plane to process. Geometry rectification of ruled slope is considered the surface as expanded surface, and the method of it can be approximated. The most common method of plane processing is discussed.

The origin of engineering coordinate system of slope can coincide with the origin of geodetic coordinate system. In the engineering coordinate system, the direction of X-axis is the horizontal direction of slope’s approximately trend and the direction of Z-axis is upward along the plumb line. Image rectification of slope must establish the slope coordinate system. In the slope coordinate system, the \(Xc\)-axis is the intersection line that between slope plane and X-Y plane of engineering coordinate system, the \(Yc\)-axis is vertical to \(Xc\)-axis and the origin is the intersection point \((O')\) between \(Xc\)-axis and the Y-axis of engineering coordinate system.

In the image rectification, we must make sure the slope formula. The slope formula can be used as that:

\[
AX + BY + CZ + D = 0
\]

The intersection point (A) between projection ray and slope is the object point on the slope which corresponds to the image point (a). Obviously, the coordinate \(A(X, Y, Z)\) of object point is calculated by (2) and (5). Because of the X-axis of engineering coordinate system may be not strict parallel with the direction of slope, there will be having some tiny distortion of slope stretched image map. Introduction of the angle \(\theta\) between X-axis of engineering coordinate system and the direction of slope will help to solve the problem. Thus, the coordinate \(A(Xc, Yc)\) of stretched image map of slope is that:

\[
\begin{align*}
X_c &= (Y-X|\tan \theta|)|\sin \theta| + X/\cos \theta \\
Y_c &= Z/\sin \alpha
\end{align*}
\]

Where, \(\alpha = \tan^{-1}((\sqrt{A^2 + B^2}/C))\), the angle is inclination of slope relative to horizontal plane; \(\theta\) is calculated by plane formula.

According to the \((Xc, Yc)\) and pixel (a), we can resample in the slope coordinate system, at last we can get the stretched image map of slope. Because of the slope is level, the stretched image map of slope is the stretched image map of slope.
4. The precision of the system

The designed excavation face of the tunnel is composed of local plane and cylindrical surface. To elaborate the precision of image-based spatial information system, the circular tunnel is taken for instance.

4.1. The precision of imaging pixel

The precision of imaging is determined by imaging distortion, detection precision of interior orientation elements and repeatability of camera imaging. Test of grid imaging shows that, when rectify symmetrical radial distortion of objective lens imaging and eccentric distortion, distortion’s residual mean square error of non-metric camera is one pixel. The error of interior orientation elements is influenced by its’ detection precision and stability synchronously. According to the test range calibration, mean square error of interior orientation elements is about 2 pixels. If considering the influence of residual error of imaging distortion and error of interior orientation elements synchronously, the mean square error of coordinate is about 2.5 pixels.

4.2. The pixel’s projection precision on target surface

We can compute object space coordinate of projection point using (1) and (2), and, mean square error of projection point in object space coordinate is concluded:

\[
\begin{align*}
    m_x &= m_{x_1}^2 + u_x^2 \lambda_1^2 + \lambda_2^2 m_u^2 \\
    m_y &= m_{y_1}^2 + v_x^2 \lambda_1^2 + \lambda_2^2 m_v^2 \\
    m_z &= m_{z_1}^2 + w_x^2 \lambda_1^2 + \lambda_2^2 m_w^2
\end{align*}
\]

(7)

where, \(m_{x_1}, m_{y_1}, m_{z_1}\) are the mean square error of pixel in image space auxiliary coordinate, we can extract them from the transformation between image space coordinate and image space auxiliary coordinate. We can calculate \(m_\lambda\) according law of propagation of error, it’s extracted from the following while \(Y_S = 0\):

\[
\lambda = \left( w(R-Z_S) + \sqrt{R^2(v^2+w^2)-(v^2(R-Z_S))^2} \right) / (v^2+w^2)
\]

(8)

depending on \(m_{x_1}, m_{y_1}, m_{z_1}\) and \(m_{z_S}\).

Take middle level tunnel for sample to acquire visual concept of projection precision: assuming the radius(W) of tunnel is 10m, format of image is 1600*1200(pixel), considering pixel on the edge of image who has worst projection precision, assuming it’s image coordinate is \(x=800, z=600\)(pixel). Mean square error of setting exterior orientation elements of image are: \(m_{x_1} = m_{y_1} = m_{z_1} = \pm 5mm\) and \(m_x = m_y = m_z = \pm 2'\), where photo instrument for geologic logging is used in tunnel. When angle of image inclination (\(\omega\)) is 45°, results obtained from (7) are: \(m_x = \pm 26mm, m_y = \pm 17mm\) and \(m_z = \pm 22mm\). Because of projection precision is changing with angle of image inclination, so, several transitional coordinate of object space are set in data processing, upper limit of inclination of image is 45°, it means that when the pixel projects to object space surface, the mean square error of projection coordinate will less than above results. When under the best projection condition, that is, the projection of center pixel whose inclination of image is zero, mean square error of corresponding coordinate of object space is \(m_x = \pm 18mm, m_y = \pm 7mm\) and \(m_z = \pm 18mm\). Therefore, when the pixel project to object surface, the actual precision should between above both, that is: \(\pm 18mm \leq m_x \leq \pm 26mm, \pm 7mm \leq m_y \leq \pm 17mm\), and \(\pm 18mm \leq m_z \leq \pm 22mm\).

4.3. The precision of stretched image map

In tunnel, projection plane of image on object space is cylindrical surface, but ultra-less digging follows with actual tunnel digging. The estimation formula for projection displacement of ultra-less digging point on circular cylindrical surface (designed excavation surface) is:

\[
\delta \approx \frac{\Delta R(R-h)\cos \omega}{\sqrt{R^2-(R-h)^2}\cos^2 \omega}
\]

(9)

where, \(\Delta R\) is depth of ultra-less digging; R is radius of circular tunnel; h is height of instrument at projection center; \(\omega\) is inclination of projection ray.
The precision of stretched image map is decided by projection error \((m_x, m_y, m_z)\) of pixel on object cylindrical surface and projection displacement of ultra-less digging synchronously. According to the existing construction specifications, assuming mean square error of ultra-less digging’s depth is \(15\text{cm}\), in above instance, under the most unfavorable projection condition, mean square error of projection displacement of ultra-less digging extracts from (9) is \(m_\theta = 147\text{mm}\). It means, the precision of stretched image map depends on projection error caused by ultra-less digging primarily.

4.4. The image-based logging precision of geologic structure lines

Logging precision of structure lines is concluded by:

\[
m_p = \pm \sqrt{m_x^2 + \left(1/(R - Z)\right)^2 m_y^2 + \left(Y/(R - Z)^2\right)^2 m_z^2} + m_\theta + m_\alpha
\]

(10)

where, \(m_\theta\) is sketching error of structure lines on stretched image map, which is influenced by quality of image, precision of layer registration and location of operating mouse. So, in above instance, even if \(m_\theta = \pm 3\) (pixel), most unfavorable precision extracts from(7) is \(m_p = \pm 151\text{mm}\), but while there is no projection displacement of ultra-less digging, the most favorable precision is \(m_p = \pm 27\text{mm}\), the actual precision of logging should between above both. Certainly, maximum of position deviation on spot is more than ten centimeters, compare with it, the image-based logging can meet precision requirement.

4.5. The precision of image-based measurement of rocks attitude

Measuring attitude of rocks on image is one characteristic of image-based geologic logging. Structure line of rocks on stretched image map is the cross line between structural plane of rocks and excavated surface of tunnel. The coordinate of pixel \((X, Y)\) on stretched image map could establish one-to-one corresponding relationships with object space coordinate of projection point. Therefore, through measuring image coordinate of three non-collinear points on structural line, space attitude of corresponding rocks is calculated.

Space mathematical model of rocks structural plane is shown as (5). When measuring more than 3 points on structural line, precision of calculating function coefficients \((m_\alpha, m_\beta, m_c)\) by indirect adjustment is concluded. Further, according to the law of propagation of errors, based on \(\alpha = \tan^{-1}(\sqrt{A^2 + B^2}/C)\) and \(\theta = \tan^{-1}(B/A)\), \(m_\alpha\) and \(m_\theta\) are calculated through \(m_\alpha, m_\beta, m_c\). The author measured several structural line of rocks at the stretched image map of circler tunnel. As a typical example, the length of them penetrates half of the wall. The results based on the system are \(m_\alpha = \pm 0.05^{\circ}\) and \(m_\theta = \pm 0.11^{\circ}\).

The precision of image-based measuring of rock attitude is changing with the form and radius of tunnel, also the length of structural line and distribution of measuring point. However, no matter how, from method of precision estimation and the above sample, we can conclude that image-based measuring of stretched image map of rocks has so high precision that it can meet precision requirement of logging.

To the above tunnel problem, system precision has been solved. The analysis method of system precision of slope and foundation pit is similar to tunnel. But the projection target surface always simplifies to plane. It can’t apply stretched image map to measure the structural surface attitude of rocks, instead stereo photos must be used. The author has expounded the system precision of slope and foundation pit in [9]. When the photo is taken at the mid-distance (25m), the logging result which is influenced by all the most unfavorable factors is \(m_p = \pm 0.36\text{m}\). When there isn’t any projection displacement of ultra-less digging, the most favorable precision is \(m_p = \pm 0.06\text{m}\). The actual logging precision is between both above.

5. Application and analysis of the system

Image-based spatial information system for geologic logging is widely used in the hydroelectric engineering, transport engineering, mining engineering and so on. Fig.5 shows the image-based geologic logging example of the circler tunnel in a hydroelectric engineering (the diameter of it is 12m), they are the logging interface which based on tunnel stretched image map and the corresponding results map of logging respectively. Fig.6 shows the image-based geologic logging example of the slope in a hydroelectric engineering, they are the logging interface which based on slope stretched image map and the corresponding results map of logging respectively.
Those images are shot by the digital camera Canon G5 which has been calibrated. The format of tunnel image is 640×480 pixel and the format of slope image is 2592×1944 pixel. In tunnel, 12 edge matching errors in image mosaic have been random examined. Because of the mean square error of the pile segment stretched image map are $1/\sqrt{2}$ times as large as edge matching error of image mosaic, the actual error of the stretched image map is that $m_p = \pm 68\text{mm}$. What needs to explain is that error of most examined points are smaller than the actual error, only very few examined points are impacted by the projection displacement which is brought by excessive ultra-less digging. In slope, 21 position errors in structure feature points of stretched image map have been random examined in different pile segment of many slopes. Most feature points are near the mosaic lines, the result of examination is $m_p = \pm 0.21\text{mm}$. The image where mosaic lines lie is always in the edge of photo format, so it has the larger impaction of ultra-less digging and the other error factors. Because of that, the mean square error of actual logging which is based on stretched image map must be smaller than the examination result. In general, each of the precision can meet the theoretical precision estimation.

6. Conclusion

Image-based spatial information system for geologic logging can improve the technology level and the work efficiency of data collecting and processing, management and applications. It also provides the image-based production for engineering construction. Technical process of image-based geologic logging decreases the risk and the labor intensity of workers, improves the automation and quality of the geologic logging results. Applying the non-metric camera to the image-based geologic logging, all of the precision have met the current requirements of engineering standard. Image-based spatial information system for geologic logging and related technology is a computer-assistant geologic logging information technology which can completely replace the current mode of manual operation.

7. References


