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Mine laneway 3D reconstruction based on photogrammetry

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Abstract: Aiming at the problem of 3D reconstruction for mine laneway, the technique route and step were given based on digital close range photogrammetry and traverse surveying. 3D coordinates of laneway traverse point, photogrammetric station, control strip points were obtained by electronic total station based on mine coordinate system. The feature points were extracted from the scene images. The camera was calibrated by direct linear transformation (DLT). 3D relative coordinates of the arbitrary feature points in mine laneway were calculated after feature points being matched, in which the origin of coordinate system is photogrammetric station. The 3D absolute coordinates of the feature points in mine laneway can be obtained by the combined adjustment of photogrammetry and non-photogrammetric observations and coordinate conversion. The measurable 3D model of the underground laneway terrain surface was constructed with the 3D coordinates of feature points on the image pairs obtained. The measurable 3D model of a corridor was reconstructed by the mentioned method and the experiment precision with an average standard deviation of 0.013 6 m between the 3D model and practical measure was obtained by electronic total station. The experimental resulted show the validity of the proposed approach.
Key words: digital mine; mine laneway; photogrammetry; 3D reconstruction; direct linear transformation (DLT)

1 Introduction

Mine laneway is the important entity in mine production activity. There are various pipelines, facilities and constructs in laneway. Traditional position of these entities is displayed in two-dimension (2D) map. Reconstructing laneway interior three-dimension (3D) landscape will provide a good platform for the digital management, analysis and operation of laneway. Meanwhile it can also be used in the management system in mine and geology for its 3D characteristics, and furthermore to promote the construction of mine informational work.

Underground structure laneway is different from the ground structure, it is not the independent entity, its shape features (surface, ridge, side) and texture features are relatively simple. Nevertheless, reconstructing the building on the ground based on image needs take photos outside of the building, while reconstructing underground passage must take photos inside the passage. For the consecutive feature of passage, it leads to the big distortion between the area of short sight and far and produce error easily.

At present, reports of 3D reconstruction based on image are mainly for ground construction. The step is that first to obtain the image vanishing points of parallels in 3D space, second, computing the interior and exterior parameters of camera, and then reconstructing 3D entity. For the example of the 3D reconstruction researches in Refs. [1−3] are all based on the acquisition of vanishing points. But it is very difficult to control the precision of acquiring vanishing points, and it is also very difficult to acquiring many vanishing points in mine laneway. In Ref. [4], the method which based on the plane position of space object and its corresponding relationship in image, reconstructing 3D entity through computing the camera's interior and exterior parameters with direct linear transformation (DLT) algorithm is presented. To some extent, this method can solve the problem of 3D reconstruction for ground entity, but it is not suit for the 3D reconstruction of mine laneway. In Ref. [5], the method is presented, which under the assumption that one initial 3D geometry model is given, camera extrinsic parameters, intrinsic parameters and parameters which determine the final 3D geometry model are obtained by interactive way using line features on subway image. Then using the principal of monocular vision theory, feature points on image is reprojected onto the 3D geometry model surface plane to get detailed 3D model.

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The precondition of this method is given that the shape features of underground passage. But, the validity of this method is restricted for the many irregular characteristics of mine laneway.

Because photogrammetry is the technology of obtaining measurable information from noncontract real imaging, it is thought of the most effective ways as measurable 3D rebuild based on images [6−7]. Aiming at the problem of 3D reconstruction for mine laneway, a new method is put forward which combining traverse surveying, digital close range photogrammetry and the real images of mine laneways obtained by camera, the measurable 3D model of mine laneways which have real texture can be reconstructed.

2 Laneway data collection, processing and fusion

Data collection is the pivotal first step for constructing measurable 3D model of mine laneway [8]. It is involved: the location data of laneway and the space and specialty attribute data of all kinds of the mine laneway appurtenance. In order to obtain the coordinate of these space data, in this work, the way that combine traverse surveying and digital close range photogrammetry is presented. That is the ways that make use of non-metric digital camera, electronic total station, and control strip point to obtain space absolute coordinate. Based on mine coordinate system, 3D absolute coordinates of laneway traverse point, photogrammetric station and other detail points are obtained by electronic total station; The real digital images of mine laneway are taken by digital camera, then the feature points are extracted and matched from the obtained images; The digital camera's interior, exterior parameters and 3D relative coordinates of control calibration strip points and the arbitrary feature points in mine laneway are determined by direct linear transformation (DLT) algorithm, in which origin of coordinate system is photogrammetric station. After coordinate conversion, the 3D absolute coordinate of all kinds of feature points in mine laneway can be obtained by the combined adjustment of photogrammetry and non-photogrammetric observations.

2.1 Obtaining 3D data with method of DLT

DLT is an algorithm whereby image coordinates are transformed directly into coordinates in the object space. Because the DLT is distinguished by the feature that no the parameters of intrinsic and exterior initial value are needed, it is suitable for processing image data obtained by non-metric cameras. However, its advantages are also pronounced when used in data reduction for photographs taken with metric cameras. In this work, after taken the laneway images which contain control strip point and satisfy image overlap demand. First, calculating the transform coefficient between object point and image point by use of control point strip's space coordinate, which obtained by electronic total station traverse survey, and corresponding image coordinate. Then, extracting feature points from obtained images and matching the correspondence points between stereo (several) images. Finally, the arbitrariness feature points' 3D coordinate were calculated by the transform coefficient. The DLT algorithm takes the following forms [9]:

$$\begin{cases} x+\dfrac{l_1X+l_2Y+l_3Z+l_4}{l_9X+l_{10}Y+l_{11}Z+1}=0 \\ y+\dfrac{l_5X+l_6Y+l_7Z+l_8}{l_9X+l_{10}Y+l_{11}Z+1}=0 \end{cases} \tag{1}$$

where x, y are the values of image points coordinates; X, Y, Z are the control strip points coordinates; l_i (i=1, 2, ⋯, 11) are the transform coefficient which relate to the parameters of exterior orientation. When there are abound observation values, there exist random errors (v_x, v_y) in image points coordinates observed and non-liner errors (Δx, Δy) of image point. The error equations can be expressed as follows:

$$\begin{cases} v_x=-\dfrac{1}{A}[l_1X+l_2Y+l_3Z+l_4+xXl_9+xYl_{10}+ \\ \quad xZ_{11}+A(x-x_0)r^2k_1+x] \\ v_y=-\dfrac{1}{A}[l_5X+l_6Y+l_7Z+l_8+yXl_9+yYl_{10}+ \\ \quad yZ_{11}+A(y-y_0)r^2k_1+y] \end{cases} \tag{2}$$

where v_x, v_y are the discrepancy of image point coordinates; x_0, y_0 are the coordinates of the principal image point; k_1 is the lens distortion coefficient in the radial direction; $r=[(x-x_0)^2+(y-y_0)^2]^{1/2}$.

Supposing $A=l_9X+l_{10}Y+l_{11}Z+1$.

The error equations and normal equations can be expressed in matrix notation as follows:

$$\boldsymbol{V}=\boldsymbol{ML}-\boldsymbol{M} \tag{3}$$

$$\boldsymbol{L}=(\boldsymbol{M}^{\mathrm{T}}\boldsymbol{M})^{-1}\boldsymbol{M}^{\mathrm{T}}\boldsymbol{W} \tag{4}$$

where $\boldsymbol{V}=[v_x \ \ v_y]^{\mathrm{T}}$

$$\boldsymbol{M}=-\begin{bmatrix} \frac{X}{A} & \frac{Y}{A} & \frac{Z}{A} & \frac{1}{A} & 0 & 0 & 0 & 0 & \frac{xX}{A} & \frac{xY}{A} & \frac{xZ}{A} & (x-x_0)r^2 \\ 0 & 0 & 0 & 0 & \frac{X}{A} & \frac{Y}{A} & \frac{Z}{A} & \frac{1}{A} & \frac{yX}{A} & \frac{yY}{A} & \frac{yZ}{A} & (y-y_0)r^2 \end{bmatrix}$$

$$\boldsymbol{L}=(l_1 \ \ l_2 \ \ l_3 \ \ l_4 \ \ l_5 \ \ l_6 \ \ l_7 \ \ l_8 \ \ l_9 \ \ l_{10} \ \ l_{11} \ \ k_1)^{\mathrm{T}}$$

$$\boldsymbol{W}=[\frac{x}{A} \ \ \frac{y}{A}]^{\mathrm{T}}$$

After the parameters l_1 through l_{11} have been solved by process of iteration, we can calculate the space coordinates X, Y, Z of any point according to the following steps:

1) The non-linearity system distortion corrections may be added respectively with the image point coordinate:

$$\begin{cases} x+\Delta x = x+k_1(x-x_0)r^2+\cdots \\ y+\Delta y = y+k_1(y-y_0)r^2+\cdots \end{cases}$$

2) The 3D coordinates X, Y, Z of object space feature points were calculated based on a pair of image.

As (x+Δx, y+Δy) are coordinates observed values, and to take into consideration random errors. Eq. (1) may also be written as:

$$\begin{cases} x+v_x+\dfrac{l_1X+l_2Y+l_3Z+l_4}{l_9X+l_{10}Y+l_{11}Z+1}=0 \\ y+v_y+\dfrac{l_5X+l_6Y+l_7Z+l_8}{l_9X+l_{10}Y+l_{11}Z+1}=0 \end{cases} \tag{5}$$

The error equations are as follows:

$$\begin{cases} v_x=-\dfrac{1}{A}[(l_1+l_9x)X+(l_2+l_{10}x)Y+ \\ \quad (l_3+l_{11}x)Z+(l_4+x)] \\ v_y=-\dfrac{1}{A}[(l_5+l_9x)X+(l_6+l_{10}x)Y+ \\ \quad (l_7+l_{11}x)Z+(l_8+x)] \end{cases} \tag{6}$$

This can be expressed in matrix form as:

$$\boldsymbol{V}=\boldsymbol{NS}+\boldsymbol{Q} \tag{7}$$

For a pair of image, where

$$\boldsymbol{V}=[v_x \quad v_y \quad v_{x'} \quad v_{y'}]^{\mathrm{T}}$$

$$\boldsymbol{N}=\begin{bmatrix} -\dfrac{1}{A}(l_1+l_9x) & -\dfrac{1}{A}(l_2+l_{10}x) & -\dfrac{1}{A}(l_3+l_{11}x) \\ -\dfrac{1}{A}(l_5+l_9y) & -\dfrac{1}{A}(l_6+l_{10}y) & -\dfrac{1}{A}(l_7+l_{11}y) \\ -\dfrac{1}{A'}(l'_1+l'_9x) & -\dfrac{1}{A'}(l'_2+l'_{10}x) & -\dfrac{1}{A'}(l'_3+l'_{11}x) \\ -\dfrac{1}{A'}(l'_5+l_9y) & -\dfrac{1}{A'}(l'_6+l'_{10}y) & -\dfrac{1}{A'}(l'_7+l'_{11}y) \end{bmatrix}$$

$$\boldsymbol{S}=\begin{bmatrix}X & Y & Z\end{bmatrix}^{\mathrm{T}} \tag{8}$$

$$\boldsymbol{Q}=$$

$$\begin{bmatrix} -\dfrac{1}{A}(l_4+x) & -\dfrac{1}{A}(l_8+y) & -\dfrac{1}{A'}(l'_4+x') & -\dfrac{1}{A'}(l'_8+y') \end{bmatrix}$$

The unknown X, Y, Z is calculated from normal equations as

$$\boldsymbol{S}=-(\boldsymbol{N}^{\mathrm{T}}\boldsymbol{N})^{-1}\boldsymbol{N}^{\mathrm{T}}\boldsymbol{Q} \tag{9}$$

2.2 Combined adjustment of photogrammetry and non-photogrammetric observed value

Combined adjustment of photogrammetry and non-photogrammetric observed value is referring to use non-photogrammetric observed value or condition in photogrammetry adjustment. In this work non-photogrammetric information includes: based on mine coordinate system, the absolute 3D space coordinates of laneway traverse hub, photogrammetric station, control strip points and other detail points which obtained by traversing. As for photogrammetric observed value in combined adjustment, is refer to the relative 3D space coordinates of laneway random feature points and control strip points which obtained by transform DLT based on closed-range photogrammetry coordinate system. The principia that confirm all kinds of non-photogrammetric observed value are to find the relationship between computational unknown in uniform Cartesian coordinates. That is determine the conversion relation between mine coordinate system and closed-range photogrammetry coordinate system which coordinate origin is photogrammetric station. Compute the 3D space coordinates of control strip points by DLT algorithm and electronic total station traversing to realize combined adjustment of photogrammetry and non-photogrammetric observed value. The absolute space coordinates of all kinds of feature points underground laneway are obtained with high precision.

3 Experiment and result analysis

In order to validate the technique route and step given above, obeying the principle from special to ordinary, experiment is carried out in the 5th floor corridor in school of Geomatics, Xi'an University of Science and Technology. After the establishing of manual marks, establishing of object coordinate system, data collection, image feature extraction and matching, 3D modeling and 3D model measuring based on OpenGL etc. The reconstruction measurable 3D model of mine laneways can be achieved based on digital close range photogrammetry.

3.1 Establishment of control field and data collection

The aim of control surveying in close range photogrammetry is bringing the close range photogrammetry network into the given object coordinate system by means of control points. Control field establishment includes the selection and establishment of manual marks and control calibration strip. The manual marks are the points laid on corridor walls. The images of taking should include a certain amount of manual marks. Measuring the image point coordinates of manual marks is the base of calculating the coordinates of object 3D points by photogrammetry. The aim of laying control calibration strip is making up the shortages of control points established with traditional way. In object coordinate system, the origin of coordinate system is the center of electronic total station, Z axis is point to the corridor, X axis is the rightward direction which perpendicular to Z axis, Y axis is the upward direction which perpendicular to *XOZ* plane. Establishment of control field and selection of coordinate system are shown in Fig. 1.

Fig. 1 Control field and selection of coordinate system

The new method that combining traverse surveying and digital close range photogrammetry is presented here. Namely, the way of combining non-metric digital camera, electronic total station, and control calibration strip. The real digital images of corridors are taken by digital camera, 3D coordinates of control calibration strip points, photogrammetric station and manual marks are obtained by electronic total station with conventional surveying method.

3.2 Feature extraction and image matching

For object 3D reconstruction based on photogrammetry, it is the key to extraction of object feature points and image matching [10−11]. Figure 2 shows the result of feature extraction from corridor real image with feature operator. Figure 3 shows the result of identical points in local position based on feature matching [12].

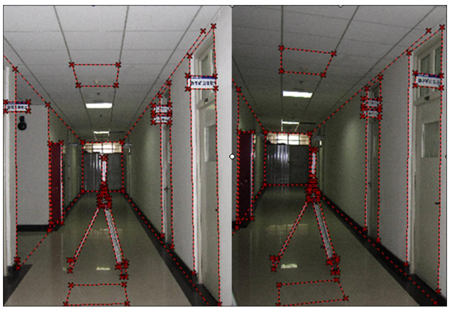

Fig. 2 Result of feature extraction

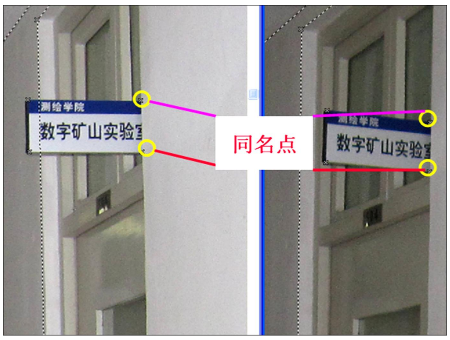

Fig. 3 Local result based on feature matching

Table 1 shows the relative coordinate of object space points, which obtained with the method of photo-

Table 1 Relative coordinate of object space points (local)

No.	*X*/m	*Y*/m	*Z*/m
1	−0.198 151	−0.018 510	−1.593 092
2	−0.171 025	−0.018 581	−1.594 489
3	−0.172 683	−0.200 989	−1.643 067
4	−1.962 620	−0.202 757	−1.633 618
5	−0.018 208	−0.326 537	−1.302 854
6	−0.045 180	−0.322 753	−1.318 634
7	−0.061 498	−0.341 694	−1.263 923
8	−0.002 310	−0.345 480	−1.246 291
9	−0.032 799	−0.013 640	−1.281 854
10	0.033 925	−0.014 133	−1.293 892
11	0.000 023	0.018 915	−1.412 587
12	−0.064 753	0.016 373	−1.396 622
13	−0.100 731	−0.337 040	−1.202 402
14	−0.124 525	−0.009 710	−1.282 402
15	−0.198 944	0.068 162	−1.563 052
16	−0.191 324	−0.221 908	−1.676 540
17	−0.114 330	−0.309 098	−1.344 701
18	−0.117 650	−0.297 102	−1.348 689
19	−0.119 266	−0.296 270	−1.346 361
20	−0.466 931	0.352 197	−2.563 411
21	−0.271 422	0.363 579	−2.617 856
22	0.152 323	−0.042 233	−1.198 605
23	−0.440 457	0.079 513	−2.540 805
24	−0.241 017	0.077 487	−2.536 715
25	0.005 877	−0.146 664	−1.328 228
26	0.010 085	−0.145 049	−1.333 847
27	0.009 762	−0.189 124	−1.341 558
28	0.009 013	−0.191 434	−1.342 429
29	0.004 524	−0.191 161	−1.343 756
30	0.004 181	−0.188 951	−1.341 635
31	0.007 021	−0.191 524	−1.342 182
32	−0.006 685	−0.196 235	−1.344 054
33	−0.010 399	−0.197 145	−1.339 710
34	−0.009 457	−0.202 348	−1.344 856
35	−0.012 397	−0.202 732	−1.343 618
36	−0013 183	−0.205 995	−1.341 615
37	0.014 144	−0.204 925	−1.346 967
38	−0.014 570	−0.211 253	−1.347 311
39	−0.002 116	−0.021 353	−1.338 980
40	0.005 033	−0.209 582	−1.329 149
41	0.004 313	0.205 190	−1.336 697
42	−0.001 766	0.204 280	−1.336 559
43	−0.004 101	−0.203 421	−1.333 234
44	−0.006 045	−0.202 380	−1.335 909
45	−0.004 630	0.196 885	−1.341 069
46	−0.014 099	−0.214 863	−1.348 602
47	−0.037 544	−0.293 428	−1.349 810
48	−0.041 869	−0.295 750	−1.344 832
49	−0.041 884	−0.299 201	−1.340 746
50	−0.433 950	0.314 141	−1.337 984

grammetry DLT in conditions of acquiring stereo pair identical points.

3.3 3D modeling and measurement

After the feature extraction, image matching, combined adjustment and absolute orientation for five pieces of corridor images, the result of corridor 3D reconstruction can be obtained with PhotoModeler [13−14]. Figure 4 shows the result of corridor 3D reconstruction. Figure 5 shows the result after texture mapping. Object point coordinate computed above is relative. To acquire the measurable 3D coordinates, the principle of photogrammetry absolute orientation can be use. First more than four coordinates of manual marks or control calibration strip points are collected by electronic total station, then seven absolute orientation parameters can be calculate, finally the relative object coordinates can be converted to the measurable 3D coordinates.

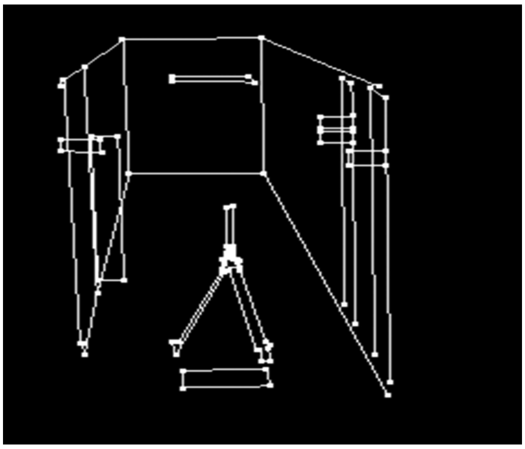

Fig. 4 Corridor 3D reconstruction

Fig. 5 Corridor 3D reconstruction after texture mapping

Comparison between the measurements of 3D model and the real measurements by electronic total station is shown in Table 2.

Table 2 Evaluation of precision

Line	PM measure/m	Practical measure/m	Absolute error/m	Relative error	RMS/ m
1	0.718	0.700	0.018	5.10	0.013 6
2	2.041	2.038	0.003	1.80	
3	3.168	3.176	0.008	0.25	
4	2.936	2.959	0.023	1.20	
5	2.304	2.316	0.012	0.50	
6	0.291	0.295	0.004	1.40	
7	0.140	0.143	0.003	2.10	
8	0.471	0.491	0.020	7.30	

4 Conclusions

1) The way of reconstruction mine laneway measurable 3D model based on photogrammetry is presented. 3D absolute coordinates of mine laneway traverse point, photogrammetric station, control point strip, and other detail points are obtained by electronic total station. The real digital images of mine laneway are taken by the non-metric camera. Extracting feature point’s and image matching from obtained images. The camera’s interior, exterior parameters and 3D relative coordinates of target point in mine laneway are calculated by DLT algorithm, in which origin of coordinate system is photogrammetric station.

2) Take a corridor that with the same feature with mine laneway for example. The measurable 3D corridor is rebuilt based on the above approach. The results show that the measure precision of 3D model and practical measure by electronic total station is the same (RMS<0.013 6 m).

3) Because the places that actual mine laneway in an unfavorable condition or circumstance, such as the shape irregular, beam dim, there are many kind of pips and establishment inside. How to reconstruction complex scene measurable 3D model is our farther work.

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