3 - D VISION SYSTEM FOR MONITORING THE SIMULATED DEFORMATION OF BRIDGE

Xinyu Yang
Civil Engineering Department
Northern Jiaotong University
Beijing, People's Republic of China
commission V

Visiting Schorlar
Department of Civil Engineering
University of Illinois at Urbana-Champaign
U.S.A.

ABSTRACT

An automatic three-dimensional photogrammetric measurement system was developed at the Northern Jiaotong University, Beijing, P.R. China. This system consisted of video camera, image processing equipment PREICOLOR-2000, made by France Numelec Company, and a program which combined image processing, pattern recognition and photogrammetric algorithms. Data acquisition, digital image recording, feature extraction, target recognition and the automatic targets matching for the left and right photos were carried out in near real-time and the computation for the three-dimensional coordinates of targets in object space were performed automatically. A small photogrammetric model was used to experiment with the accuracy of this system. An accuracy of 0.30, 0.23 and 0.39 mm, about 1/2700 of photographic distance D, was achieved for measuring the X, Y, and Z coordinates of object points. The experimental results showed that the posterior compensation algorithm for DLT equations developed by the author can compensate the systematic errors effectively and much higher accuracy can be achieved for vidicon imagery. The practical application presented concerns the tentative experience for applying this system for monitoring the simulated deformation of a bridge

INSTRUCTION

Recent advance in solid-state cameras, digital image processing and computer techniques, combined with the increasing needs for three-dimensional vision for robots in industry, has given impetus to the development of digital and real-time close-range photogrammetry. These new challenging areas of research have become the focus of photogrammetrist attention in recent years.

The development of close-range photogrammetry in the past ten years has shown that photogrammetry possesses some special characters compared with other methods as used for precise measurement for industrial application. This technique is specially suitable for the measurement of movements of a large number of points taking place in an instant, particularly for the moving object or structure in dynamic state which are difficult to measure using a direct or contact method. However, since the conventional photogrammetric techniques acquire dada on the basis of photos, the working cycle takes a significant time interval between photographing and the final results. Thus it is impossible to know the results at the moment when the movement or deformation have taken place. In most of engineering processes, this limits the application of close-range photogrammetry. Unfortunately, most of the research carried out in China in the past years still remains at the laboratory level, and even in the most applicable situations the conventional close-range photogrammetry have not been widely used.

Now the development of microcomputers and solid-state cameras has come to the stage to compete with the traditional expensive photogrammetric instruments with their increasing accuracy, capacity and falling prices. Their advantages over traditional instruments can be clearly seen in tendency. Photogrammetry has developed from analogue to analysis, and will develop rapidly from analysis to digits. Traditional costly and complicated equipment and the dull and repetitive observation will certainly be replaced by the intelligent computers and solid-state cameras. Digital and real-time photogrammetry is really an exciting area of research which has a broad prospects. It will open up the way for close-range photogrammetry to get widely used in industrial automation, automatic processing control and intelligent robots.

An all-digital and near real-time close-range photogrammetric system was developed at Northern Jiaotong University, Beijing, P.R. China. This system consisted of image processing equipment, PREICOLOR- 2000, made by France Numelec Company, vidicon cameras and software which combines image processing, pattern recognition and photogrammetric algorithms. The software has the function of image digitalization, feature extraction and the automatic location of the image coordinates of targets. The image coordinates of targets on the left photo and its corresponding image on the right photo are automatically matched and the three-dimensional coordinates of unknown points in the object space are calculated according to the photogrammetric mathematical model. This system was used to monitor the simulated deformation of a bridge and the satisfactory results were achieved.

SYSTEM DESCRIPTION

The main part of a real-time photogrammetric system includes cameras, image encoder, image memories, software and hardware for image processing, host computer and output peripherals. This system should have the ability for image processing with very high speed. The main functions of image processing involve image enhancement, edge detection, feature extraction and pattern recognition.

On the basis of equipment available at Northern Jiaotong University, a France made image processing system, PREICOLOR-2000, was used as the main equipment and supporting software was developed. The main functions of the system and the image processing procedure are introduced in this section.

(1) Main Equipment

The PREICOLOR 2000 is a multiprocessor and multibus image processing system, equipped with high capacity memories, made by France NUMELEC company. Its main parts are as follows.

- The operation system of the host computer is UNIX, supporting PLM 86 and FORTRAN high level languages. Management processor is an 8086 16-bit processor.
- High-speed processor for image handling and processing enables access to all the image and graphic memory (22 megabytes) via two address buses and two data independent buses.
- Multibus system enables data and program transfer between processors and peripherals. This system accepts input signal from up to four different cameras simultaneously.
- 512 x 512 video processor for image memory. Four images of 512 x 512 pixels each. (optional 1280 x 1280 video processor).
- Specialized processors for linear or non-linear point transformations and convolution, and over 300 software functions for image processing.
- External peripherals include hard discs, magnetic tape unit, graphic tablet, ink-jet color printers and digital optical disc.

(2) Image Processing

The main operations of image processing for real-time application involve noise reduction, feature enhancement, target recognition, image point location and point matching. These operations are available on most of current image processing systems.

The main operations are described as follows.

1. Noise reduction and Feature Enhancement

The purpose of noise reduction is to reduce electric noise in the bias frame, while feature enhancement is for the emphasis on the geometric feature of targets. The experiment showed that PERICOLOE-2000 was well shielded and no electric noise was found on the bias frame. Under a good condition of illumination and sharp contrast between targets and the background, good imagery was obtained. Considering that any operation of enhancement may lose the original information of image, the operations of noise reduction and image enhancement were omitted from the operations.

2. Image Binary Operation

In order to facilitate the feature extraction, the binary operation was performed on the image at first. Since the influence of illumination, the gray levels of the area around each target are different. Therefore, the image is divided into windows and then a threshold is selected for each window separately by using cluster analysis method.

3. Feature Extraction and Target Recognition

For the determination of image coordinates of target center, the geometric feature of targets must be extracted from binary image. After scanning on the binary image, δ-adjacent left direction priority algorithm was used to trace out the geometric boundary of each target one by one. According to the arrangements of targets and the number of targets on each row, targets were recognized and labeled.

4. Accurate target location

The accuracy of image coordinates obtained by the boundary tracing is only one pixel. Sub-pixel accuracy can be obtained by interpolating the gray levels of adjacent pixels around a point or by the polynomial approximation method. In this experiment, an one-dimensional normal divergent polynomial was used to locate the exact position of points on boundary. The exact image coordinates of a target were obtained by computing the centroid of points on the boundary.

5. Matching

Two photos are taken from two different positions for an object. These two photos consist of a stereopair which contains the three-dimensional coordinate information of the object. For calculating the three-dimensional coordinates of the object according to the photogrammetric model, each point in one photo must be matched with its corresponding point on the other. There are two methods for point matching. One is suitable for targeted object, which needs the priori knowledge about the number and arrangement of targets. The other uses the digital correlation techniques for point matching, for which targets are not necessarily used. The detail methods were given by Wong & Ho (1986) and El-Hakim (1986).

For monitoring purpose, targets are usually used to identify points to be measured. In this case, the former method is very simple and reliable for point matching and takes much less computing time. Therefore, it was used in this experiment.

TEST FIELD

A high accuracy photogrammetric test field was set up in this experiment for following objectives:

- to experiment with the achievable accuracy and reliability with this all digital and real-time system.
- to evaluate the accuracy of image point location with different algorithms.
- to study the characters of systematic errors resulted from vidicon cameras used for digital and real time application.
- to determine the exterior and interior orientation elements of the cameras.

The volume of the test field is 40 x 40 x 12 cm^3. There are altogether 46 targets well-distributed on 6 planes, the heights of which are 0, 20, 40, 65, 90 and 120 millimeters respectively. For the stability of the test field, a piece of 6-mm glass was used as a base board. The measurement and photographing for the test field were performed under air conditioning.

The targets were made by photographic method. The geometric figure of each target is shown in Fig.4. The figure consists of a square measuring 14 mm each side and a circle measuring 6-mm in diameter in the middle of the square. The center of this target is represented by a small circle and a dot which measures o.5 and 0.1 mm in diameter respectively.

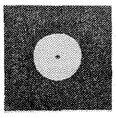

Fig. 1

The center of the target should be easy to measure. The target size was such that it could be displayed at least in 5 x 5 pixels or more on the image plane so that there were enough data used for sub-pixel interpolation.

Instead of a three-dimensional coordinate, which is very expensive and rarely used in China, an optical jig borer TP 4280, made in Beijing, China (Fig. 5), was used for the measurement of the three-dimensional coordinator of the targets of the test field, The travel distance of the borer is 1000, 890 and 700 mm in X, Y and Z direction respectively. The precision of X, Y coordinate readings is 0.001 mm and the accuracy for point location is o.o1 mm.

The plane coordinates of X and Y and elevation Z were measured independently. A KarlZeiss optical sighting device with 40 X magnifying power was used for aim at the the center of target in the measurement of X and Y coordinates. A gauge was used for the measurement of Z coordinate. An accuracy of 0.01 and 0.05 mm was achieved for measuring the plane coordinates X,Y and the elevation Z for the test field respectively.

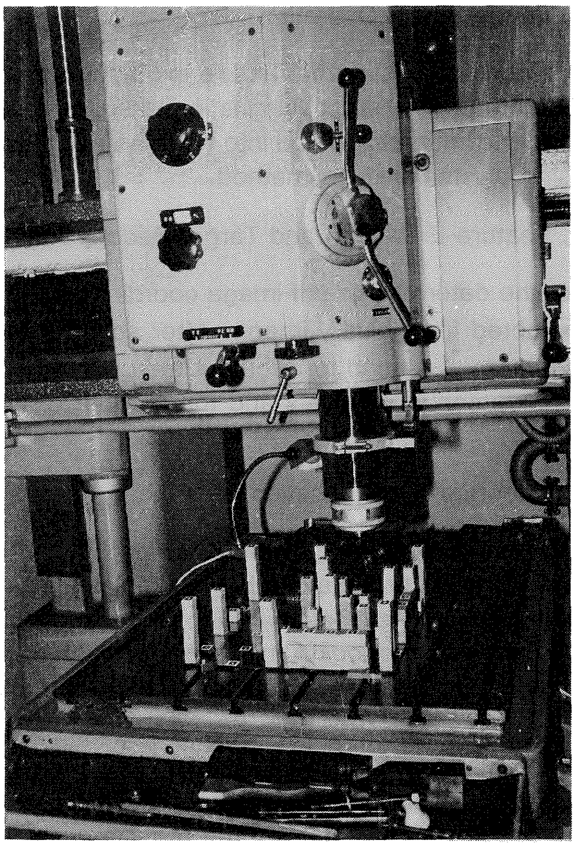

Fig. 2

BEXPERIMENT DESIGN

The goal of this experiment is to determine the achievable accuracy and reliability with all digital and real-time system for automatic measurement of three-dimensional coordinates of stable points or moving points in object space. This system could be used for monitoring the deformation of a space structure or for tracing the moving object in real-time.

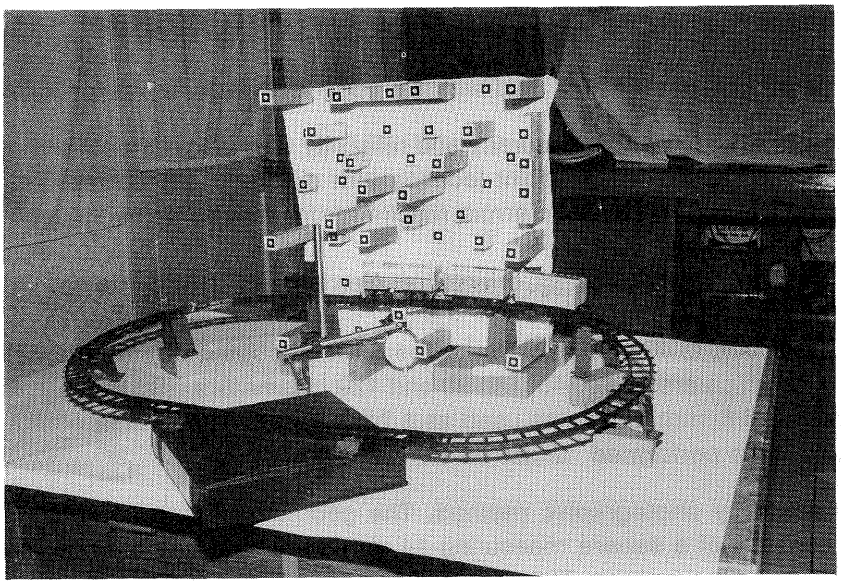

Fig. 3

In recent years, the flexible pier techniques have made advance as being used for the design of railroad bridges in China. So far, there are no perfect methods for the measurement of movements of the top of the pier and for the deformation of the beam when the train runs through the bridge at very high speed. To study the feasibility of monitoring the dynamic deformation of the bridge with the digital and real-time system, a railroad round track model was designed as shown in Fig. 3.

In Fig. 4 it can be seen that a round track goes through the lower part of the test field. The test field was used concurrently as the control system for photogrammetric measurement. In the middle of the bridge beam, point No. 90 was used for presenting the deformation of the bridge. A dial gauge was installed under point No.90 to check the accuracy of the photogrammetric results.(Fig.4) Two photo pairs were taken for the bridge when it was at the dead load state and when the train was riding on it. The three-dimensional coordinates of point No.90 at two states were obtained with the this automatic measurement system. The coordinate difference between them are the deformation values of the the bridge.

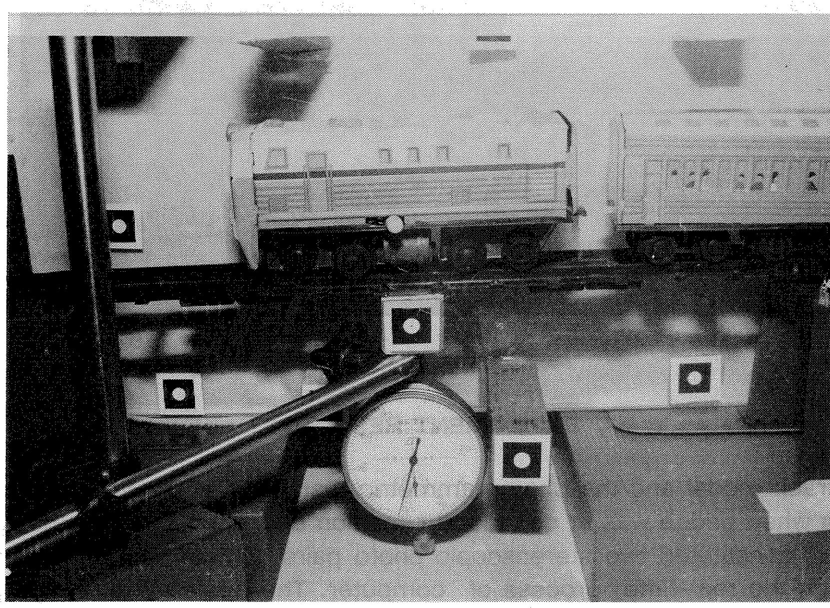

Fig.4

The test field was also used as an object to be photographed for the determination of achievable accuracy with this system and for the evaluation of systematic errors of vidicon cameras.

Photogrammetric Configuration

The field angle 2β of the vidicon camera was about $19°$ calculated from object space data, and the width of the object to be photographed was 40 cm. In order to get even accuracy for the X, Y, and Z directions, and for the 100% overlap of the photos, convergent photograph was used. The optimum configuration angle α_0 and convergent angle ϕ_0 were calculated with the field angle 2β as a parameter according to the formula given in references (9) and (11). The optimum base B_0 and object distance D_0 were calculated according to α_0 and ϕ_0 and the width of object. The results are shown in Table 1.

Table (1)

2β	α_0	ϕ_0	U	V	B_0 (m)	D_0 (m)
19°	33.9°	32.9°	2.820	2.086	1.128	0.834

Camera

An ordinary vidicon camera equipped with MINONDA MD 20 mm, 1:2.8 lens was used in this experiment. (Fig. 10) The camera stand was driven by two stepping motors. The orientation angles ϕ , ω , κ and the coordinates X, Y and Z of the camera were controlled by a single board computer.

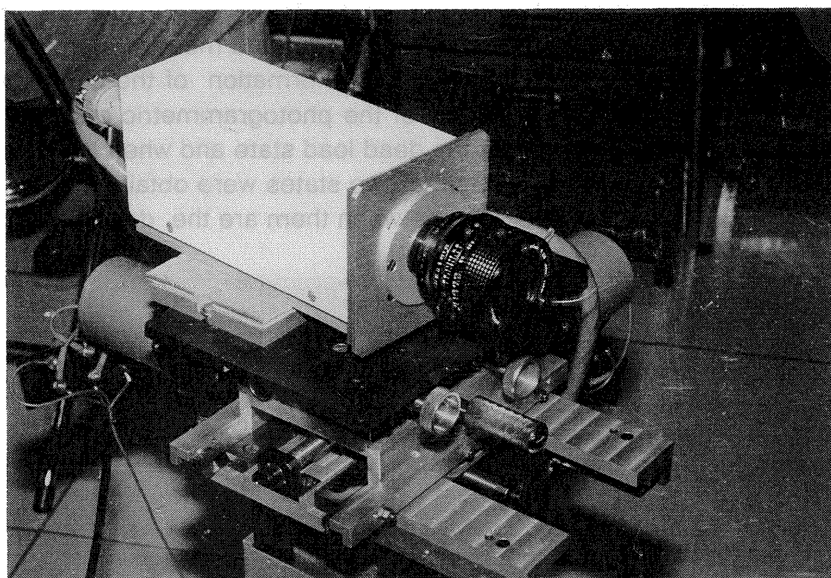

Fig. 5

EXPERIMENT RESULTS

The train around-track model and the photogrammetric test field were used as test objects. Four images were taken when bridge was at dead load condition and when train was riding on the bridge. These four images constituted two stereoscopic photo pairs. Object space coordinates of targets were gained through the real-time process of computer. The operation of image processing took about 1 minute and the operation of photogrammetric calculation took only 9 seconds. Further improvement on the software for image processing can save much of CPU time.

(1) Experiment Accuracy

The achived accuracy of system is shown in Table 2. The values of RMSE are the root mean square error of the differences in coordinates obtained by photogrammetric method compared with photogrammetric test field.

Table (2)

Number of Photopair	Number of Targerts	Number of Check Points	RMSE (mm)			
			MX	MY	MZ	Mr
I	29	14	0.296	0.253	0.464	0.606
II	28	14	0.309	0.211	0.363	0.483

Point No.90 located at the middle of the beam was used to monitor the deformation of the bridge. The coordinates of point No.90 obtained by photogrammetric system are shown in Table 3.

Table 3

State	X	Y	Z	ΔX	ΔY	ΔZ
Dead Load	285.363	200.020	72.706	0.043	-2.083	-0.271
Train Riding	285.403	197.937	72.435			

The value of the movement of point No.90 in Y direction measured by a dial gauge was – 2.405 mm. The difference between photogrammetric measurement and the gauge measurement was 0.322 mm. Two methods got consistent results.

(2) Effect Analysis on Posterior Compensation

DLT equations applied for analytical computation for non-metric cameras impelled the the development and wide application of close-range photogrammetry. In the recent 10 years, many people worked for the improvement of DLT algorithm for further increasing the accuracy of non-metric cameras. For example, the 11 parameter solution (Bopp & Krause,1978) and non-linear solution (McGline 1984). But the actual accuracy was only slightly improved.

For the self-calibration, the DLT basic equations may be extended in such a way as to include some added parameters to absorb the effect of remaining systematic error. However, the experiment results showed that the systematic errors of vidicon images differed from one to one. It is impossible to obtain a mathematical model universally suitable for all images. Unsuitable models for systematic error will seriously degrade the accuracy of self-calibration. Moreover, it is very difficult to select the systematic error model by testing the significance of added parameters using statistical method because of the correlation of the 11 L parameters.

The principle of the posterior compensation algorithm for DLT equations was given by the author in reference (10). The posterior compensation algorithm for DLT equations gets round the difficulties for selecting the systematic parameters. Statistical tests are used for the judgment of significance of systematic errors according to the residuals from adjustment. Only when the systematic errors are affirmed, can polynomials be used for fitting the residuals. When the residuals only contain random errors, the least squares estimates are the optimum values. In this case, if polynomials are used for fitting the residuals, some systematic effects may arise from curve fitting due to the systematic propagation of random errors. Thus a threshold can be chosen for the automatically refinement of image coordinates for every different images, with which the program runs over and over until the optimum estimates are obtained.

This method used for processing the vidicon imagery in this experiment was very effective. Table 4 and Table 5 display the computation results without posterior compensation and with compensation respectively. From Table 4 and Table 5, it can be seen that the posterior compensation can improve accuracy more than 99%, 124% and 40% in X, Y, and Z direction and the RMSE of point position can improve 80%.

χ^2–test and T–test were used to test the significance of systematic errors of the image coordinates. For the polynomials used to fit the residuals of image coordinates, second degree or third degree terms can be chosen. Table (6) displays results of different terms.

In this experiment, the author also experimented with the accuracy of self-calibration. Brown model (1964, 1965) was used to compensate the systematic errors.The number of unknowns carried in the DLT solution depends on how much systematic errors are corrected for. Thus, the total number of unknowns carried in self-calibration solution, that is 11 DLT parameters plusing the coefficients for lens distortion, could be chosen as 12, 14 and 16 respectively. Table 7 displays the results of different choice of unknown numbers for self-calibration method.

CONCLUSIONS

This experiment dealt with the application of all digital and real time photogrammetric system for monitoring dynamic processes. In this experiment, the author studied the systematic error characters of vidicon imagery and methods for systematic error compensation. Posterior compensation method and self-calibration method were used in this experiment. The computation results are shown in Table 5, Table 6 and Table 7, from which we get the following results,

PHOTOPAIR BB34 TABLE 4

POINT	GIVEN			COMPUTED		
	X	Y (mm)	Z	X	Y (mm)	Z
22	411.152	468.364	89.888	411.082	468.268	90.017
25	168.431	464.763	90.275	167.850	463.802	90.637
35	137.870	420.584	1.287	137.397	419.908	.781
41	469.858	383.615	24.246	469.811	384.053	24.561
44	255.850	379.535	120.262	256.984	380.235	119.858
62	409.835	305.391	44.954	409.795	305.401	44.899
63	334.440	310.412	91.022	335.111	310.880	90.673
64	255.866	303.500	1.514	256.242	303.887	1.542
65	173.844	304.838	43.392	173.948	305.100	44.067
66	99.812	302.233	120.340	99.239	302.675	120.264
81	466.316	150.588	120.080	465.423	149.804	119.778
84	252.636	147.892	90.157	252.903	147.392	90.382
85	169.396	147.055	1.917	169.383	147.071	1.651
86	100.012	149.982	120.131	100.205	150.245	120.359
23	332.656	464.494	1.215	332.496	463.947	2.434
24	255.008	463.791	21.539	255.139	463.059	21.784
32	376.926	418.448	42.055	377.498	418.849	42.384
33	294.881	419.822	1.183	295.485	419.978	1.778
34	215.494	420.852	91.687	216.181	421.356	91.562
42	412.614	386.760	1.101	412.571	387.196	1.842
43	334.076	383.259	90.028	335.046	383.783	89.860
51	374.262	337.400	120.478	375.133	337.709	120.007
52	285.266	333.663	43.043	285.959	333.997	42.793
53	210.107	338.891	21.800	210.577	339.385	21.518
71	471.916	245.330	1.540	470.757	245.021	1.552
72	418.218	224.694	1.474	416.978	224.486	1.909
75	171.175	226.400	1.825	171.030	226.667	1.312
90				285.807	197.862	72.460

MEAN SQUARE ERRORS (mm)

DX = .615 DY = .473 DZ= .428 DR = .886

PHOTOPAIR BB34 TABLE 5

POINT	GIVEN			COMPUTED		
	X	Y (mm)	Z	X	Y (mm)	Z
22	411.152	468.364	89.888	410.979	468.226	90.003
25	168.431	464.763	90.275	168.160	464.653	90.287
35	137.870	420.584	1.287	138.097	420.676	1.172
41	469.858	383.615	24.246	470.112	383.834	24.242
44	255.850	379.535	120.262	256.343	379.834	119.883
62	409.835	305.391	44.954	409.520	305.061	44.926
63	334.440	310.412	91.022	334.408	310.452	90.933
64	255.866	303.500	1.514	255.834	303.537	1.545
65	173.844	304.838	43.392	173.811	304.727	44.255
66	99.812	302.233	120.340	99.609	302.185	120.109
81	466.316	150.588	120.080	466.338	150.630	120.100
84	252.636	147.892	90.157	252.650	147.884	90.275
85	169.396	147.055	1.917	169.316	147.038	1.396
86	100.012	149.982	120.131	100.144	150.013	120.339
23	332.656	464.494	1.215	332.350	464.248	1.858
24	255.008	463.791	21.539	254.995	463.563	21.537
32	376.926	418.448	42.055	377.163	418.639	42.184
33	294.881	419.822	1.183	295.163	420.008	1.523
34	215.494	420.852	91.687	215.915	421.405	91.416
42	412.614	386.760	1.101	412.513	386.959	1.348
43	334.076	383.259	90.028	334.365	383.357	90.018
51	374.262	337.400	120.478	374.425	337.239	120.519
52	285.266	333.663	43.043	285.374	333.598	42.840
53	210.107	338.891	21.800	210.322	339.120	21.668
71	471.916	245.330	1.540	471.352	244.895	.991
72	418.218	224.694	1.474	417.220	224.422	1.349
75	171.175	226.400	1.825	170.938	226.311	1.423
90				285.403	197.937	72.435

MEAN SQUARE ERRORS (mm)

DX = .309 DY = .211 DZ= .306 DR = .483

Table 6

RSME (mm) MX	MY	MZ	Mr	Number of Times for Compensation	RSME of Residules	Tx	Ty	χ^2_x	χ^2_y	Compensation Polynominals
0.615	0.473	0.428	0.886	0	0.721	0.0021	0.0048	68.6052	87.4434	Second Degree
					0.588	0.0043	0.0037	65.0076	38.7256	
0.337	0.252	0.330	0.535	1	0.263	0.0017	0.0003	14.9086	5.8676	Second Degree
					0.335	0.0001	0.0008	20.8192	12.8140	
0.320	0.255	0.332	0.527	2	0.257	0.0013	0.0011	14.4754	5.3825	Second Degree
					0.324	0.0015	0.0019	19.4902	12.0466	
0.346	0.218	0.324	0.522	1	0.249	0.0014	0.0011	13.8437	4.6974	Third Degree
					0.315	0.0007	0.0005	19.5882	10.1023	
0.319	0.208	0.308	0.490	2	0.242	0.0011	0.0004	13.4296	4.1703	Third Degree
					0.301	0.0012	0.0005	17.6239	9.6261	
0.309	0.211	0.306	0.483	3	0.240	0.0010	0.0001	13.2184	4.0784	Third Degree
					0.299	0.0019	0.0008	17.3762	9.5298	

Tabe 7

RSME MX	MY	MZ	Mr	Number of Unknows
0.614	0.482	0.426	0.889	12
0.591	0.488	0.340	0.839	14
0.834	0.746	0.521	1.240	16

- χ^2- test is an effective method for statistical test on systematic errors.
- T - test is ineffective for testing the significance of systematic errors in image coordinates since the lens distortion and other similar systematic errors have a symmetrical distribution.
- For vidicon imagery, accuracy obtained by incorporating a third -degree polynomial is better than a second-degree polynomial.
- For vidicon imagery, the systematic errors of image coordinates are different in x, y direction.
- Compared Table 6 with Table 7, it can be seen that self-calibration method was less effective and less reliable than posterior compensation. Unsuitable systematic error model seriously degraded the accuracy of self-calibration.

ACKNOWLEDGMENT

The author extend special thanks to Prof. Kam W. Wong for his invaluable comments for improving this paper. This experiment was finished at the Northern Jiaotong University, Beijing, P.R. China with the assistance of Mr Yidong Huang. The image processing work of this experiment was finished with the assistance of Ph.D graduate student Jincheng Li. The image processing equipment PERICOLOR-2000 used in this study belonged to the Institute of Information Science, Northern Jiaotong University. The cooperation provided by Prof. Baozong Yuan of that institute is gratefully acknowledged.

REFERENCES

(1) Abdel-Aziz, Y.I. and Karara, H.M., Direct Linear Transformation from comparator Comparator Coordinates into Object-Space Coordinates, Proc. ASP/UI Symposium on Close-Range Photogram metry, Urban, IL, 1971.

(2) Bopp, H. & Krauss H., Extension of the 11-parameter Solution for On- the-Job Calibration of Non-Metric Cameras, International Archives of Photogrammetry, Vol. 24, Part 5/1, York, 1982.

(3) El-Hakim, S.F., A Real-Time System for Object Measurement with CCD Cameras, International Archives of Photogrammetry and Remoter Sensing, Vol.26, Part 5, pp. 363-373, 1986.

(4) Karara,H.M. and Chen, L.-C., Optimization of Non-metric Analytical Close-Range Photogram metric Networks, International Archives of Photogrammetry and Remote Sensing, Vol. XXV, Part A5, 1984.

(5) Marzan, G.T., Doctoral Dissertation. Rational Design for Close- Range Photogrammetry. University of Illinois at Urbana-Champaign, 1976.

(6) McGlone, J.C., Use of the MACO 35/70 in Close-Range photogrammetry, International Archives of Photogrammetry, Vol. 24, Part B-5, 1984

(7) Wong, Kam W. and Ho, Wei-Hsin, Close-Range Mapping with a Solid State Camera, Photogram metric Engineering and Remote Sensing, Vol. 52, No. 1, pp. 67-74, 1986.

(8) Wong, Kam W., Stereo Solid State Camera Systems, International Archives of Photogrammetry and Remoter Sensing, Vol.26, Part 5, pp. 454-458, 1986.

(9) Yang, Xinyu, Master Thesis,The Optimum Configuration of Close-Range photogrammetry, Nor thern Jiaotong University, 1982.

(10) Yang, Xinyu, Two-Medium Photogrammetric Measurement of movements around a Tunnel Model, Acta Geodetica et Cartographica Sinica, Vol.16, No.4, 1987.

(11) Zhu, Chenlin and Yang, Xinyu, The Optimum Configuration of Convergent Case of Close-Range Photogrammetry, Acta Geodetica et Cartographica Sinica, Vol.12, No.2, 1983.