PRACTICAL TESTING AND EVALUATING OF THE EOS PhotoModeler®, AN OFF-THE-SHELF DIGITAL CLOSE RANGE PHOTOGRAMMETRIC SOFTWARE PACKAGE

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PREFACE

In order to make our extensive series of technical reports more readily available, we have scanned the old master copies and produced electronic versions in Portable Document Format. The quality of the images varies depending on the quality of the originals. The images have not been converted to searchable text.

PREFACE

This report is a result of a research project conducted by the author during a one-year research leave from Kumming University of Science and Technology, China. Dr. Wolfgang Faig supervised the research for the report. Support was provided by the China Scholarship Council and by the University of New Brunswick.

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ABSTRACT

In the current digital era, digital close range photogrammetry is finding more ways than ever for extracting geometrical information from the objects by photogrammetry, by merging with related technologies such as CAD, digital image processing, computer graphics and 3-D modeling. Digital close range photogrammetric software based on this and aiming at non-photogrammetric environments is consequently acquiring a fast increasing market. In this project, a successful low-cost digital close range photogrammetric software package PhotoModeler® Pro (PM Pro), developed by EOS Systems Inc. in Canada is evaluated. The evaluation is based on practical tests with related analysis and discussions, concerning the software's photogrammetric performance with non-metric images, mainly in terms of accuracy, reliability and flexibility, as well as for a general outlook.

The practical testing was carried out with three different types of non-metric images and two different test fields. The images include scanned hard copy images and digital camera images taken with two different low-cost digital cameras. The two test fields include a small object, namely a 3-D metal plate, and a large object namely a wooden house. 3-D control points with high precision are uniformly distributed on both test fields. The preparations of the test fields are first briefly introduced, followed by the tests, analysis, discussions, conclusions and suggestions.

The evaluation was accomplished by testing and analyzing the results from different control configurations, different images, different objects, and different adjustment options. The photogrammetric performance and outlook of PM Pro are generally promising according to the tests. Optimum strategies for applying PM Pro to the measurements of small and large objects with two different types of non-metric images are investigated and presented. The software's requirements and limitations in control points, initial parameters and coordinate systems for processing non-metric images are given. The defects of PM Pro found in the tests, and their practical solutions or theoretical discussions are presented. Suggestions for further improvements of this software or other similar software are made, based on corresponding theoretical discussions. Some analysis and discussions are of general value in addition to the evaluation for this software, such as the suggestion of the photo-variant approach as the camera calibration scheme for non-metric cameras, the need of compensating for the systematic image errors caused by scanning and by digital image's radiometric properties, and the suggestion and proof of the pseudo camera concept. Some issues worth of further investigations are suggested, including the reasons for which the accuracies from digital camera images are significantly higher than those from scanned hard copy images, and the merging of close range photogrammetry with GIS.

PM Pro is a flexible tool of close range photogrammetric measurement in non-photogrammetric environments, while the knowledge of photogrammetry is still helpful for making full use of such software.

Key words: digital, close range photogrammetry, software package, testing, evaluation.

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Chapter 1 Introduction

1.1 Background and Objectives

With the irreversible development of photogrammetry into the digital era, close range photogrammetry is acquiring a fast increasing market by merging with related technologies such as CAD, image processing, computer graphics and 3-D modeling, for the applications of extracting geometric information from the objects. The object size ranges from as small as biological cells to as large as high buildings and archaeological sites. Designers of close range photogammetric software are therefore faced with a great opportunity and also the challenge of taking their position among competitive software systems. The digital close range phototgrammetric software package named PhotoModeler® Pro developed by EOS Systems Inc. in Canada is one of the successful examples of finding the way to the current market. Having been utilized by users in the fields of accident reconstruction, architecture, animation etc, this low-cost package has earned a series of positive comments from different customers. In this project, PhotoModeler Pro is tested with different non-metric imageries and test fields to investigate its photogrammetric performance for non-metric imageries in terms of accuracy, reliability, and flexibility, and to analyze some related theoretical problems. The results from a number of tests are generally promising for the ratio of features vs. the cost of the software package, while some theoretical clarifications and suggestions are made as the author's personal opinion.

1.2 Major Features of PhotoModeler Pro

PhotoModeler Pro (PM Pro) is a 32bit windows program that runs on Windows 95+ and Windows NT 4.0+. It supports images larger than 16MB (EOS, 1997). The latest version of the program was upgraded from 3.0j to 3.1 on 29 April 1999 just before the completion of this report, the version mainly used in this project was 3.0j, while the changes in the evaluation caused by this upgrading were mentioned.

Since PM Pro is intended to be provided to users in a vast range of fields other than in photogrammetry, the terminologies, user manual, instructions and tutorials are therefore all deliberately designed for non-photogrammetrists, which is found to be a good and basically successful attempt to win a larger market. From a photogrammetric point of view, the major features include:

1. Multiple input and output data formats compatible with most of the related current data formats, including image format, text format and CAD format ;
2. Image coordinate measurement performed by manual single point marking on a computer screen at sub-pixel accuracy where image resolution allows it, no explicit image coordinate values required, no stereo vision involved;
3. Applicable to metric or non-metric camera imageries, taken either by calibrated or non-calibrated cameras, while initial camera parameters are required to be provided either by the user or by the program default values, and a separate software named Camera Calibrator is provided for camera calibration;
4. Help tools available for image correlation, including highlighting of the identical points during point marking, epipolar lines to help in marking identical points on curved lines, cylinder correlation tool, and a semi-automatic point correlation tool

called Unreferenced Point Weld helping to correlate points after a previously successful adjustment;

5. Multiple choice options for adjustment, including photo orientation, self-calibration and camera parameters modification;
6. 3-D view available for both control point file and adjusted full points set, active connections between marked image points and corresponding points in 3-D viewer are also available;
7. Direct measurement of 3-D coordinates, distances, areas of triangle elements in object space, from the marked points on displayed images (and also in 3-D viewer for version 3.1) after successful adjustment;
8. Different precision indicators available after successful adjustment, including the precision values indicating the post adjustment double standard deviations of the object space coordinates, program designed "point tightness" values related to the link tightness of the point with the corresponding photographs and camera stations, "residual markings" in the form of vector bars at the marked points of displayed photographs indicating the point residuals resulting from the adjustment;
9. Different output forms available according to what the user needs, which include table text forms for the analytical results of 3-D coordinates and camera parameters, ortho photos on selected planes and adjusted 3-D models with or without photo texture for CAD or animation;
10. Effective helping tools, including a step by step animation tutorial movie with example projects and images, detailed help text file under the help manual,

suggestions and trouble shooting instructions both in the User Manual and in program running processes, as well as the fast responding post sale services.

1.3 Report Outline

Six chapters are designed in this report to present the tests and evaluation of PM Pro and to discuss the related theoretical and practical issues in a clear hierarchy.

Chapter 1 introduces the background and objectives of the research, and also the major features of the software package PM Pro from a photogrammetric stand point. The report outline and the main contributions of this research are also presented in Chapter 1.

Chapter 2 presents the preparation of two test fields and the acquisition of the images adopted in this project. The test field preparation includes an introduction to the test fields and the control methods and accuracies for the 3-D control points distributed on the test fields. The image acquisition includes the design and execution of the photographic missions, and the extraction of the final images adopted for the tests.

The major tests and related discussions for evaluating PM Pro are included in Chapter 3 and Chapter 4. Chapter 3 deals with the evaluation with a small test field, namely a 3-D metal plate. The evaluation was made by testing and analyzing different control configurations, different control frame simulations, different types of images (scanned hard copy images and digital camera images), and different schemes for self-calibration. The evaluation with a large test field, namely a wooden house, is presented in Chapter 4. Five digital camera photographs were used in the tests with the large test field.

In addition to the evaluations presented in Chapters 3 and 4, various other operational concerns were addressed, for proper use of or further improvements to PM

Pro or similar software. Some of these concerns are not fully covered by the texts provided by the software designer, others need further theoretical discussions. Chapter 5 includes the major operational concerns.

Conclusions and suggestions are presented in Chapter 6, which include remarks on the photogrammetric performance and general outlook of PM Pro, accuracies obtainable with non-metric images, recommended strategies for applying PM Pro to the measurements of small and large objects with two types of non-metric images, current defects of the software and recommended practical solutions or theoretical discussions, suggestions of applications, including potential applications, and suggestions for further improvements.

1.4 Contributions

This research accomplished extensive practical testing and evaluation of the software package PhotoModeler Pro. A general result of the evaluation is presented on PM Pro's photogrammetric performance for measuring objects of two different typical sizes with different non-metric images. Optimum strategies for the applications of PM Pro for practical measuring projects with non-metric images are tested, and corresponding suggestions are made. The advantages, potentials, as well as defects of PM Pro are investigated and presented, and some suggestions for further improvements are given. Theoretical discussions are made for some problems encountered in the tests. The suggestions for improvements and the theoretical discussions are valuable not only to the software under investigation, but also to the design or improvement of other similar software. Similar testing and evaluating for this currently competitive and representative software or for other similar software is not found in publications. The particular contributions of this research are mainly in the following aspects:

- The range of reliable accuracies in object space obtainable when using PM Pro for 3 different types of non-metric images and two different objects is determined. The accuracies are acceptable to many practical applications.
- Different strategies for obtaining best accuracies when applying PM Pro are tested, revealed and presented, including the optimal control configurations in terms of the numbers and distributions of control points; suggestion of a photo-variant approach as non-metric camera calibration scheme, which suggests an improvement of a program default option in PM Pro; repeated processing for scanned hard copy images, which suggests a need of compensating for the systematic image errors caused by scanning.
- Obvious differences between the results from digital camera images and from scanned hard copy images are revealed and presented. The main differences lie in that significantly higher accuracies can be obtained from digital camera images than from scanned hard copy images in PM Pro under the same conditions, and that the accuracies of the results from digital camera images are not very sensitive to changes of the number of control points, neither to the repeated processing with PM Pro. These differences can be an encouragement to the use of the fast developing digital cameras in photogrammetry, while they also imply the need for investigating the reasons.
- A promising potential of merging close range photogrammetry with GIS by employing PM Pro's feature of direct measurements on digital photos is realized and suggested.

- Uncertainties in solving for the orientation parameters with PM Pro were found in the tests and are presented.
- The concept of pseudo camera is developed and proved, and also applied in the tests. This concept explains in a clear mathematical way, about the relations between a 3-D object of photography and its final image formed by zero to multiple additional 2-D perspective transformations starting from the original image. The concept clarified the confusions in the text for PM Pro and other publications where the orientation parameters solved from the final images are mis-matched with the original cameras.

Chapter 2 Test Objects and Photography

2.1 Test Fields and Control

Two 3-D test fields with well distributed high precision 3-D control points constructed in the Department of Geodesy and Geomatics Engineering (GGE) at the University of New Brunswick (UNB) were used as the test objects for this project. The sizes of the two objects are typically representative for the relatively common sizes of small objects such as handy mechanical parts and large objects such as small houses or industrial structures.

The small test field is a square metal plate of about 17cm x 17cm with 25 12mm to 37mm long bolts fixed vertically onto the plate plane (Figure 2.1). 36 grid intersection points are engraved evenly on the plate to form 25 squares, and the 25 bolts are centered within each of the squares. Black lines, approximately 1mm wide, were used to mark the grid intersection point positions and the point positions on top of each bolt, thus to provide a good photographic contrast against the white background.

An Electronic Coordinate Determination System (ECDS) consisting of 2 one-second electronic theodolites (Kern E2) interfaced with an IBM PC computer was used to determine the 3-D object space coordinates of the 61 target points marked on the plate (36 grid intersections plus 25 bolts) in an arbitrary 3-D coordinate system. The precision (average standard deviation) of the resulting coordinates was 0.02mm, 0.03mm and 0.02mm in X, Y and Z directions respectively. Figure 2.2 shows the point numbering of the plate object.

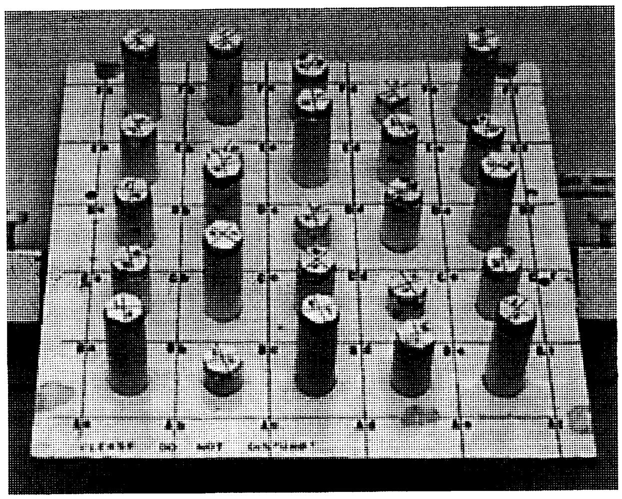


Figure 2.1 Small test object: metal plate with bolts (after Li [1999, p.114])

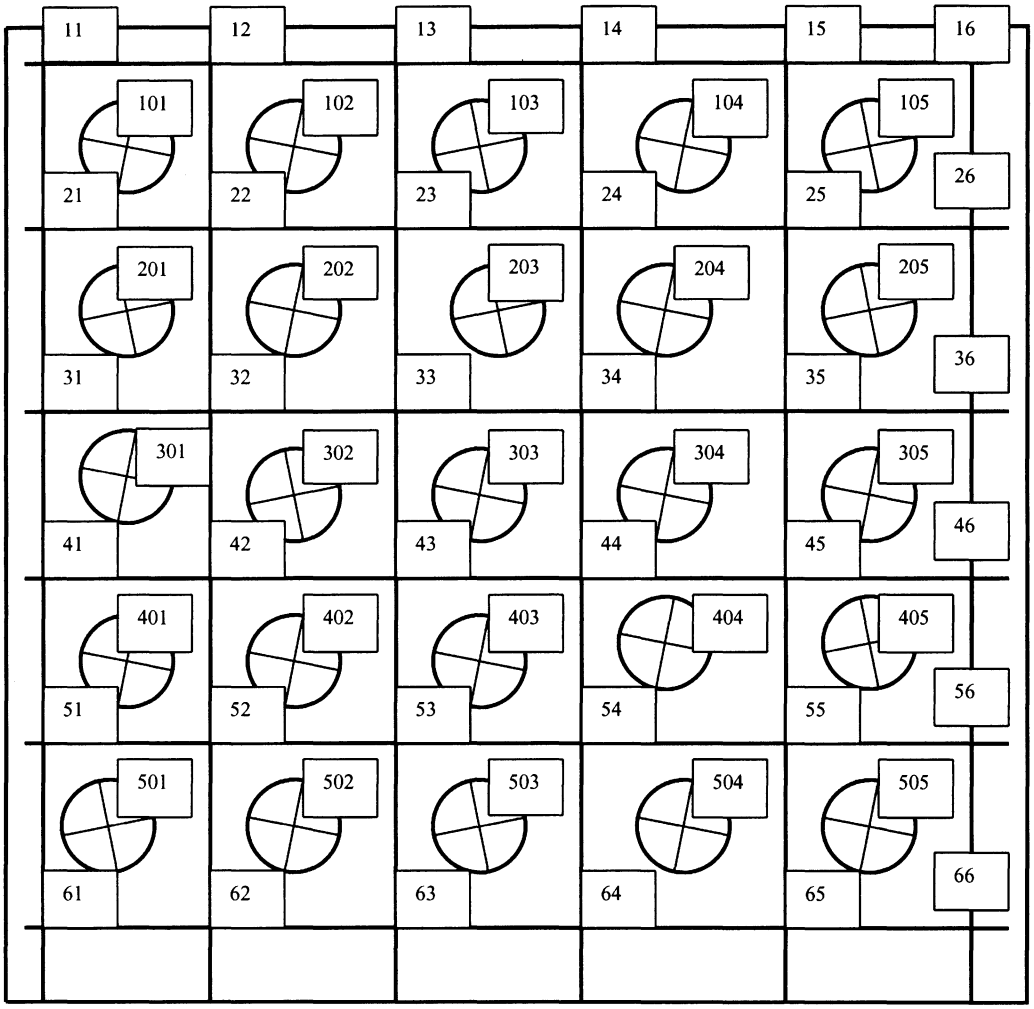


Figure 2.2 Point numbering of the metal plate object

The large test field is a white wooden house located on the UNB campus. Four joining walls on the backside of the house were used as the test field (Figure 2.3). 49 evenly distributed point positions were marked by black paper marks of 7cm in diameter on the four walls. Figure 2.4 shows the point numbering. The four walls occupy a 3-D range of approximately 7m x 8m in planimetry and 4m in height.

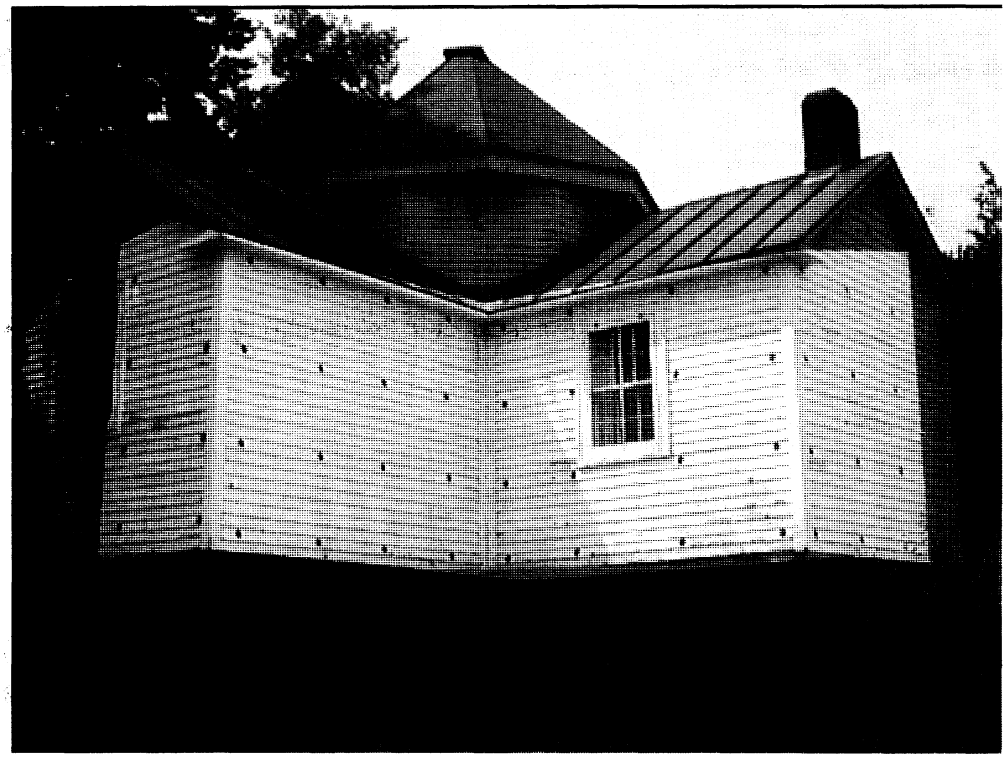


Figure 2.3 Large test object: wooden house with target points (from Li [1999, p.123])

The 3-D object space coordinates of the 49 points were determined to the precision of 0.7mm, 0.6mm and 0.1mm in X, Y and Z directions at the 95% confidence level by precise theodolite intersection with a five station 3-D geodetic adjustment.

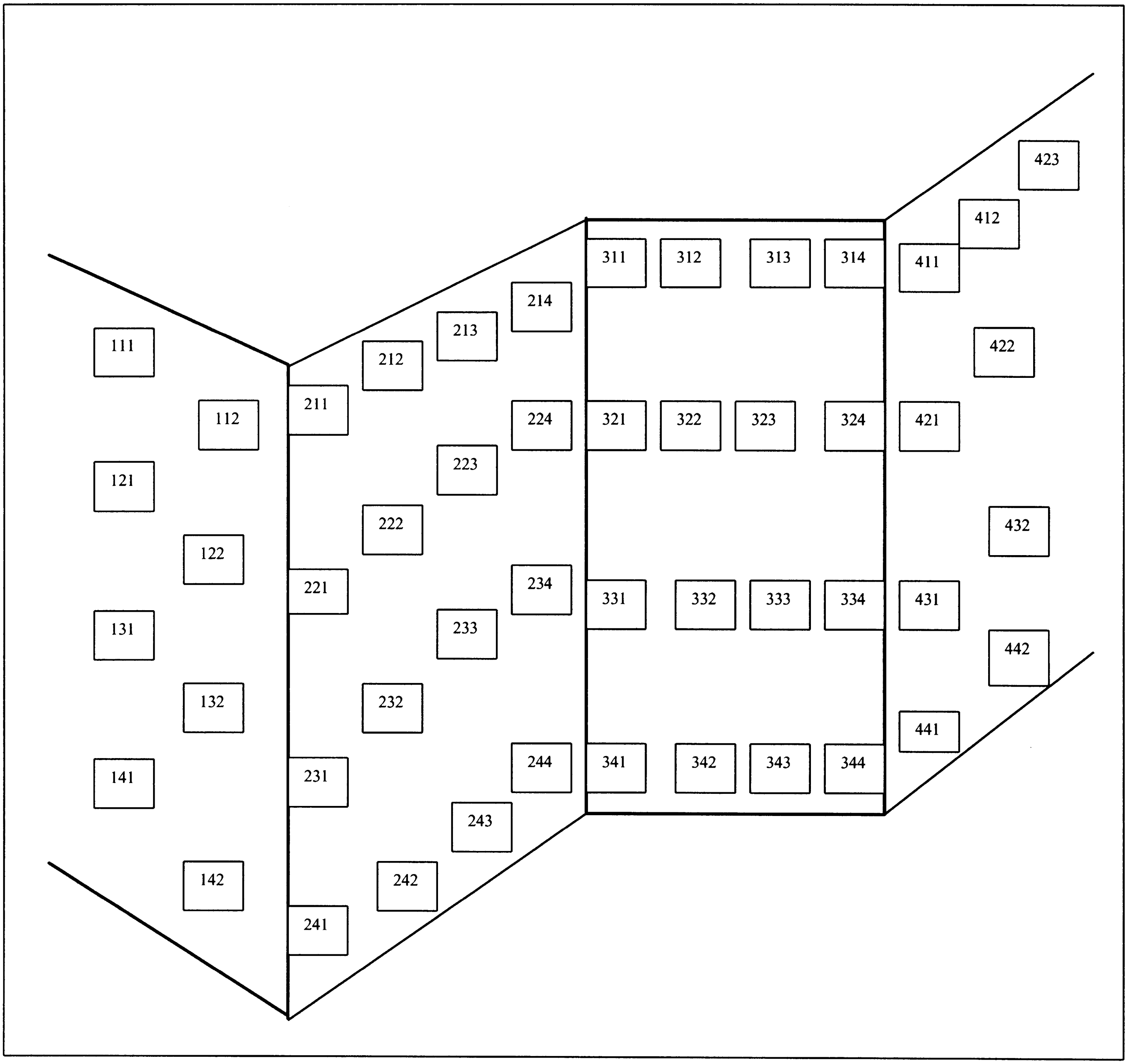


Figure 2.4 Point distribution and numbering on the wooden house

2.2 Photography

The photography was performed with three different non-metric cameras: a Fujix DS-100 digital camera, a Kodak DC-50 digital camera and an Olympus OM 10 film based camera. The main features of the two low cost and low-resolution digital cameras are listed in Table 2.1.

Table 2.1 Main features of the 2 low-resolution digital cameras (from Li [1999, p.109])

Camera	Fujix DS-100	Kodak DC-50
Number of pixels	640 x 480	756 x 504
Pixel size	9.7 um	9.0um
Lens	f= 8 ~ 24 mm	f = 7 ~ 21 mm
f-stop/shutter speed	1/4~1/750sec. F2.8~11 ISO 100	1/16~1/500sec. F2.5~24 ISO 100
Storage medium	1MB proprietary card: 5/10/21	1MB internal: 7/11/12 PC card type I/II
Interface to computer	Card reader through SCSI port	Serial port / PC card slot

Note: Number of photos can be stored under the high-/standard-(/economy-) resolution modes.

The Olympus OM 10 is equipped with a lens of 50mm nominal focal length and 36mm x 24mm format, the f-stop ranges from 2.8 to 22. A Kodak Elite 400 diapositive color film was used as the recording medium. The images on the film ware scanned into digital form because the PM Pro requires digital image import. The scanning was carried out by a Nikon scanner for slides with a scanning resolution of 59 DPMM (Dots Per Millimetre), and the final resolution for the output images was 101.7 P/mm (Pixels Per Millimetre), resulting in 9.8μm x 9.8μm pixel size. The format of the scanned image was chosen to be 1.325cm x 1.000cm, which led to a change of the scanned image scale from the original film.

For both the plate object and the house object, full or nearly full overlap convergent photography with proper intersection angles was adopted for the photography of all of the 3 sets of photographs taken with the 3 cameras respectively. Full coverage of the photo frames with the test objects was attempted to obtain large photo scales, which is important for good accuracy, while image distortions at the edge areas of the photos need to be handled effectively, especially for non-metric images.

Two sets of photographs of the metal plate with the same camera configuration were taken with the film based Olympus OM10 camera and the digital camera Kodak DC-50 respectively, with each set having 3 convergent photographs of 100% overlap taken with the same camera. In order to keep the same configuration for the two cameras, the cameras were fixed on a support frame while the plate was rotated by an angle of approximately 60 degrees between the succeeding exposures for each photo set, which was equivalent to the configuration of moving the cameras while the object was kept fixed as shown in Figure 2.5. The object distances were approximately 0.6m. Indoor laboratory lighting was adopted for all of the six exposures to provide a uniform illumination over the plate.

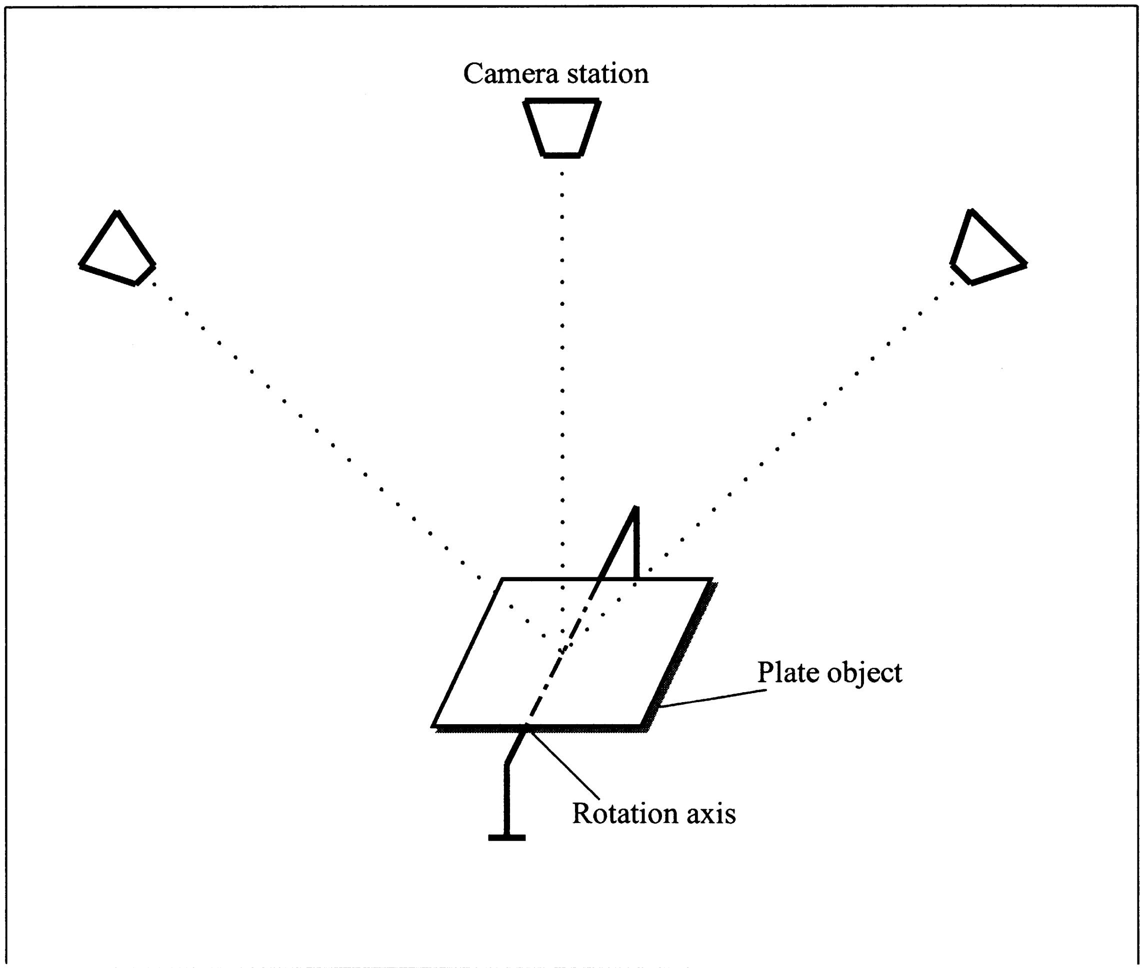


Figure 2.5 Equivalent photographic configuration for the metal plate

Five photographs of the architectural test object (wooden house) were taken with the digital camera Fujix DS-100. Figure 2.6 illustrates the photographic configuration.

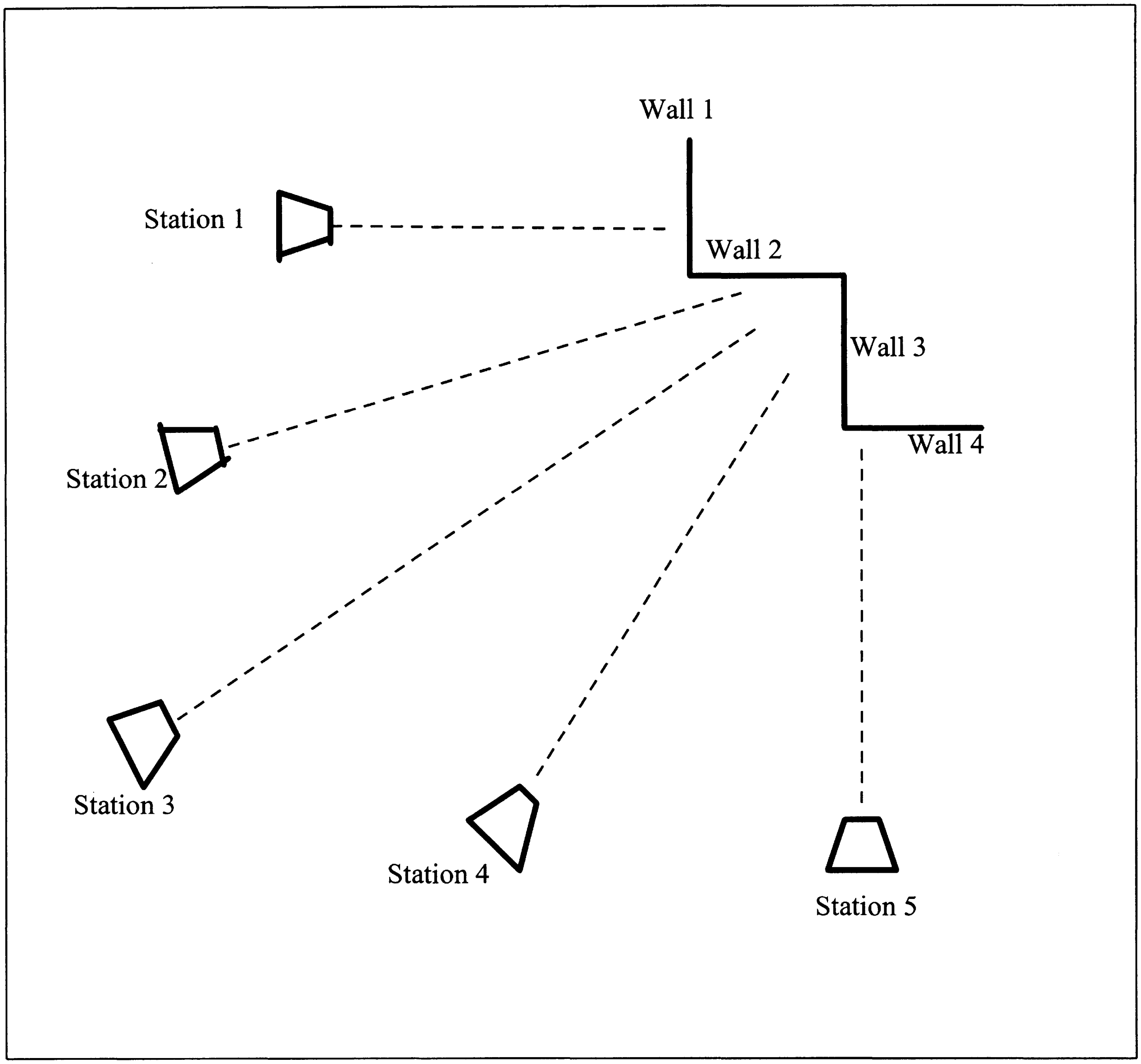


Figure 2.6 Photographic configuration for the wooden house (after Li [1999, p.124])

Due to the obstructions among the four walls in the photographs, only the photograph taken at station 3 has a complete image of all the four walls (picture in Figure 2.3), 2 or 3 walls were missing on each of the four photographs taken at the other 4 camera stations. The object distances from the cameras vary from 7m to 13m, in order to obtain maximum photo scale for good accuracy while keeping the proper convergent angles and overlaps. Natural daylight was adopted as the photographic illumination.

All of these photographs were taken on different earlier occasions for other projects in the Department of GGE at UNB, and complete photographic information was available. They were selected and adopted for this project for the purposes of saving duplicating work and testing the applicability of the PM Pro to the existing photographs, which is not uncommon in close range photogrammetric applications, especially for the applications with non-metric images.

Chapter 3 Small Test Field Evaluation

In general, the evaluation of the software package PM Pro was performed by processing the digital images obtained as described in Chapter 2 using different control configurations, different options in the adjustment, and different image combinations, and then comparing and analyzing the results. This was done to acquire the range of accuracies obtainable for the corresponding non-metric images and control configurations commonly used in practical applications, the effect of the major options provided in the program on the results, and to find out some of the existing limitations or defects both for practical and theoretical situations. It was expected that a relatively complete picture of the accuracy, reliability and flexibility of the software package could be drawn from the evaluation. Some practical solutions and theoretical suggestions or explanations for the existing problems were also to be developed from the analysis and the evaluation.

The evaluation with the small test field of the metal plate is presented in Chapter 3, and the evaluation with the large test field of the wooden house is presented in Chapter 4.

3.1 Different Control Configurations and Corresponding Accuracies

Ten different control configurations of the plate model were tested with PM Pro. The configurations were classified into two categories, namely well (uniformly) distributed control points, and control frame simulations. The former is the traditional and ideal pattern of control originally designed for mapping purposes while the latter is a specific strategy of control in close range photogrammetric applications. Some other arbitrary control configurations were also tested, but the results are omitted from this report since they conform with the results from the selected 10 configurations. From the tests with different control configurations, mainly the following practical questions for using PM Pro were to be answered:

- a). Minimum number of control points required by the software;
- b). Accuracy ranges for the two categories of control configurations;
- c). Affects of the number of control points on the resulting accuracy and practical recommendations of optimal numbers of control points;
- d). Accuracy differences between different control frame patterns and the optimal recommendation for control frames;
- e). Accuracy differences between the results from the scanned hard copy images and those from digital camera images;
- f). Effects of the camera calibration function provided by PM Pro on the resulting accuracy.

3.1.1 Well Distributed Control Configurations

3.1.1.1 Test Cases and the Results

Five well-distributed control configurations with different numbers of control points (8, 14, 19, 24 and 28) were tested using the plate model. The 3-D control points were distributed uniformly in the whole object space in each of the five case. For each set of the adjustment result, a corresponding object space coordinate comparison was made between the known control coordinates and the calculated coordinates of all check points (treated as unknown points). Thus the discrepancies in X, Y and Z respectively as well as the RMS (Root Mean Square error) values in X, Y and Z can be determined and can serve as the accuracy indicators.

Table 3.1 is part of the output of a coordinate comparison program written by the author, showing the original control coordinates, calculated coordinates of the check points, coordinate discrepancies, RMS, and the maximum discrepancies with the corresponding point ID. The data in Table 3.1 are from the test of the control configuration with 14 well distributed control points plus 47 check points treated as unknown points. The details for all of the other control configuration tests for both of the plate and the house test fields are omitted to avoid unnecessary length of this report, while the RMS values and maximum discrepancies are provided in the report.

Table 3.1 Coordinate comparison output for the configuration of 14 well distributed control points and 47 unknown points (in cm)

READ-IN CONTROL PT. ID AND COORD:

11	-7.02267	6.26431	4.95720	62	-4.78811	-3.63379	-6.45056
12	-4.01821	6.04477	4.98877	63	-1.80779	-3.86782	-6.44436
13	-1.07136	5.82457	5.00488	64	1.18780	-4.09212	-6.42147
14	1.91498	5.60217	5.01661	65	4.18301	-4.31728	-6.41832
15	4.91791	5.37500	5.03616	66	7.21111	-4.52967	-6.41003
16	7.93295	5.15833	5.03998	101	-5.89314	2.32935	6.21462
21	-7.16238	4.33426	2.68707	102	-2.88200	2.11058	6.25763
22	-4.17480	4.09784	2.70796	103	.21362	2.81286	5.42812
23	-1.21899	3.88374	2.71854	104	3.25966	3.57828	4.61245
24	1.76735	3.65381	2.73485	105	6.09865	1.42889	6.25801
25	4.77543	3.43590	2.73743	201	-5.91726	1.30615	3.12843
26	7.79104	3.21674	2.74696	202	-2.87199	2.08845	2.32897
31	-7.30677	2.39468	.39577	203	-.00811	-.06762	3.96547
32	-4.33292	2.15816	.41494	204	3.06940	.66099	3.19700
33	-1.36633	1.94263	.43859	205	6.05679	.43221	3.18594
34	1.62106	1.71528	.45214	301	-6.12192	-.60682	.86994
35	4.62542	1.50366	.46368	302	-3.17049	-1.77670	1.67122
36	7.64322	1.28870	.46854	303	-.01812	-.07229	.06676
41	-7.44877	.43182	-1.91441	304	2.94714	-1.29957	.87843
42	-4.48570	.21782	-1.88541	305	5.82027	-2.44761	1.68562
43	-1.51739	-.00668	-1.85995	401	-6.20508	-2.54002	-1.40066
44	1.46627	-.22526	-1.82409	402	-3.31402	-3.71952	-.61321
45	4.47006	-.43640	-1.81608	403	-.25539	-3.02925	-1.43261
46	7.48615	-.64888	-1.80273	404	2.85397	-2.25506	-2.22445
51	-7.58791	-1.47133	-4.17557	405	5.72348	-3.42388	-1.39160
52	-4.63362	-1.70088	-4.17128	501	-6.43749	-5.42259	-2.90766

53	-1.66740	-1.95189	-4.16994	502	-3.30219	-3.71456	-4.54588
54	1.32523	-2.18172	-4.17337	503	-.49820	-5.86891	-2.88572
55	4.32415	-2.41261	-4.17156	504	2.65570	-5.14917	-3.71103
56	7.35035	-2.64530	-4.17566	505	5.54934	-6.34346	-2.89717
61	-7.72524	-3.42159	-6.46439				

READ-IN CALCULATED PT. ID AND COORD:

12	-4.09283	5.98486	4.96502	65	4.18479	-4.34438	-6.30100
14	1.89838	5.56305	5.00152	66	7.27752	-4.58394	-6.31248
16	8.05159	5.15304	5.01763	101	-6.01708	2.66891	5.94521
21	-7.22543	4.25407	2.70255	102	-2.94425	2.45887	5.99022
22	-4.24535	4.03927	2.70934	103	.21709	3.04196	5.25129
23	-1.26379	3.83895	2.72781	105	6.35178	1.74613	6.02916
24	1.75666	3.62620	2.71720	201	-6.01164	1.50522	2.96718
25	4.80826	3.41658	2.72821	202	-2.93018	2.16438	2.25022
26	7.89801	3.18438	2.75058	203	.02412	.23128	3.68389
32	-4.39405	2.10219	.45967	204	3.16382	.86047	2.99482
33	-1.41090	1.89707	.46396	205	6.24076	.59869	3.00692
35	4.63754	1.46986	.47010	301	-6.20675	-.43905	.69599
41	-7.48224	.37053	-1.81859	302	-3.21831	-1.49623	1.39185
42	-4.54408	.17165	-1.80135	304	3.02912	-1.12361	.69257
43	-1.55413	-.03787	-1.79582	305	6.06242	-2.22438	1.41901
44	1.47311	-.24352	-1.78283	401	-6.27980	-2.38125	-1.54279
45	4.50335	-.46438	-1.77781	402	-3.35816	-3.46879	-.90168
46	7.58892	-.68981	-1.78147	403	-.24889	-2.87505	-1.60190
52	-4.68180	-1.74558	-4.03924	405	5.88596	-3.29650	-1.58922
54	1.31102	-2.21499	-4.08429	502	-3.34249	-3.66143	-4.54427
55	4.33353	-2.42784	-4.10474	503	-.47093	-5.67620	-3.16393
61	-7.73010	-3.45021	-6.25150	504	2.71028	-5.02491	-3.88248
62	-4.82327	-3.65399	-6.27833	505	5.74467	-6.17413	-3.22126
63	-1.84917	-3.88663	-6.28467				

RMS IN X, Y, Z, AND 3D RMS:

RMS X	RMS Y	RMSZ	3D RMS
.08953	.15004	.16093	.23754

RESULTED DISCREPANCIES IN X,Y,Z:

PT.	DX	DY	DZ	PT.	DX	DY	DZ
12	-.07462	-.05991	-.02375	65	.00178	-.02710	.11732
14	-.01660	-.03912	-.01509	66	.06641	-.05428	.09755
16	.11864	-.00529	-.02235	101	-.12394	.33956	-.26941
21	-.06305	-.08019	.01548	102	-.06225	.34829	-.26741
22	-.07055	-.05857	.00138	103	.00347	.22910	-.17683
23	-.04480	-.04479	.00927	105	.25313	.31724	-.22885
24	-.01069	-.02761	-.01765	201	-.09438	.19907	-.16125
25	.03283	-.01932	-.00922	202	-.05819	.07593	-.07875
26	.10697	-.03236	.00362	203	.03223	.29890	-.28158
32	-.06113	-.05597	.04473	204	.09442	.19948	-.20218
33	-.04457	-.04556	.02537	205	.18397	.16648	-.17902
35	.01212	-.03380	.00642	301	-.08483	.16777	-.17395
41	-.03347	-.06129	.09582	302	-.04782	.28047	-.27937
42	-.05838	-.04617	.08406	304	.08198	.17596	-.18586
43	-.03674	-.03119	.06413	305	.24215	.22323	-.26661
44	.00684	-.01826	.04126	401	-.07472	.15877	-.14213
45	.03329	-.02798	.03827	402	-.04414	.25074	-.28847
46	.10277	-.04093	.02126	403	.00650	.15420	-.16929
52	-.04818	-.04470	.13204	405	.16248	.12738	-.19762
54	-.01421	-.03327	.08908	502	-.04030	.05313	.00161
55	.00938	-.01523	.06682	503	.02727	.19271	-.27821
61	-.00486	-.02862	.21289	504	.05458	.12426	-.17145
62	-.03516	-.02020	.17223	505	.19533	.16933	-.32409
63	-.04138	-.01881	.15969				

NUMBER OF POINTS USED FOR RMS: 47

Largest discrepancies (absolute values)
in X, Y, Z respectively:
POINT 105 MAX. DX= .253131
POINT 102 MAX. DY= .348289
POINT 505 MAX. DZ= .324086

Generally, the accuracy of the unknown points can be improved as the number of control points increases, on the other hand however, increasing the number of control points causes increased measuring work and cost. Furthermore, the effect of improving accuracy becomes trivial when the increase in control points reaches a certain level. It is therefor worthwhile to find out an optimal way from the trade off.

Table 3.2 shows the accuracy of the check points resulting from five different well-distributed control configurations of the plate object. The images used for obtaining the results were the scanned images from hard copies (the three film photographs). The results obtained by using the digital camera images showed a similar tendency but higher accuracy, which will be presented in section 3.2.

Table 3.2 Check point accuracy for well-distributed control configurations

Case	Number of points		RMS (mm)				Max. discrepancies (mm)		
	control pt	check pt	X	Y	Z	3-D	DX/pt	DY/pt	DZ/pt
1	8	53	1.06	2.75	2.37	4.33	3.73/105	6.06/105	7.78/505
2	14	47	0.90	1.50	1.61	2.38	2.53/105	3.48/102	3.24/505
3	19	41	0.55	0.91	0.86	1.37	1.46/505	1.74/402	1.98/502
4	24	37	0.45	0.39	0.45	0.75	1.06/305	0.79/402	0.98/101
5	28	33	0.41	0.43	0.43	0.73	1.08/305	0.81/302	0.98/505

Failures of the adjustment occurred when less than 8 control points in one adjustment project or less than 7 control points on one photograph were used in the PM Pro for both of the scanned hard copy images and digital camera images. This indicated the minimum number of control points required by the software for processing non metric images taken with un-calibrated cameras.

Another accuracy indicator used in this project was obtained from distance comparisons. The comparisons were made between the distances determined by the control coordinates and the same ones determined by the calculated coordinates of the check points. Ten distances were arbitrarily selected in each control configuration to determine the distance errors. Table 3.3 shows the results of the distance comparisons.

Table 3.3 Distance accuracy of 5 well distributed control configurations

Case	Number of points		Number of distances	Average distance (cm)	Distance error					
					Discrepancy (cm)			Relative error		
	Control points	Check points			Max.	Min.	Avg.	Max.	Min.	Avg.
1	8	53	10	13.400	0.442	0.018	0.1133	1/30	1/833	1/432
2	14	47	10	13.569	0.177	0.036	0.1043	1/90	1/435	1/174
3	19	41	10	13.375	0.163	0.006	0.0863	1/81	1/2195	1/377
4	24	37	10	12.901	0.137	0.014	0.0675	1/114	1/1073	1/311
5	28	33	10	13.137	0.121	0.019	0.0590	1/103	1/1355	1/781

3.1.1.2 Analysis of Results

1. Minimum number of control points: For processing non-metric images taken with un-calibrated cameras, the software requires a minimum of 8 3-D control points for each individual adjustment project, and a minimum of 7 3-D control points on each photo.
2. Accuracy improvements achieved by increasing control points and the limitations: It can be clearly seen from Table 3.2 that the accuracy of the check points does improve with the increased number of control points when the number of control points is less than 24. But when there are more than 24 control points, increasing the number of control points does not show significant improvement in accuracy. This result verified what had been generally expected before the evaluation. Figure 3.1 shows the relations between the accuracy of the check points and the number of control points. The horizontal axis in Figure 3.1 represents the number of control points used in the adjustment and the vertical axis represents the 3-D RMS values of the check points solved by the adjustment.
3. Optimal numbers of control points: Although the software works with a minimum of 8 control points, a practically optimal range of the number of well distributed control points for an individual adjustment project could be recommended to be 15 to 25. For best accuracy, 20 to 25 control points should be provided, while more than 25 control points would be an unnecessary waste.
4. Areas of poor accuracy on photograph: The maximum discrepancies in X, Y and Z are all found at the points near the corner or edge areas of the photographs, which indicates much more significant influences of the image distortions in these areas and

the limitations of the software to compensate for these distortions. Central areas on the photographs are therefore recommended for measuring purposes when high precision is required.

5. Distance accuracy: It was found that the relative errors in each case vary in such a wide range that the average relative accuracy for each case has little significance. For the individual relative accuracy, the highest of 1/2195 was found in case 3 with a distance of 13.167 cm and the lowest of 1/30 in case 1 with the distance of 9.021 cm. The reasons are believed to lie in the limited number of distances used and the arbitrary movements of the points as a result of the adjustment. The average relative accuracy was therefore not considered to be representative for the accuracy of the corresponding control configurations. The maximum and the average discrepancies of the distances in each case on the other hand, show a close conformity with the accuracy tendency delineated by the coordinate RMS illustrated in Figure 3.1. Figure 3.2 shows the relations of the maximum and the average discrepancies of the distances vs. the corresponding number of control points.

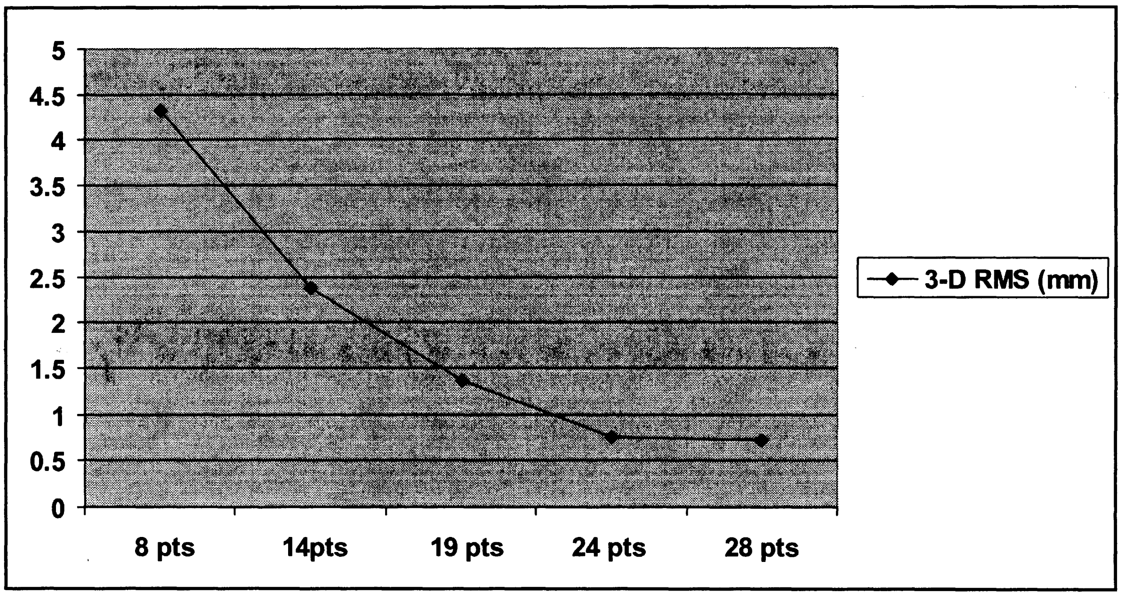


Figure 3.1 Check point accuracy and number of well distributed control points

Although the average values of the relative distance errors do not show the expected high precision, the average distance discrepancies of less than 1.2mm achieved for all of the 5 cases do indicate a practically acceptable accuracy for many engineering applications with objects having a size similar to the plate test model. Considering the facts that the line width marking the points on the plate is approximately 1mm and the existence of some blurring image in the upper-right corner area of photos 2 and 3 due to insufficient depth of field, the 3-D distance discrepancies of less than 1.2mm on average are reasonable. It is expected that the accuracy will improve with improvements in target marking and image quality.

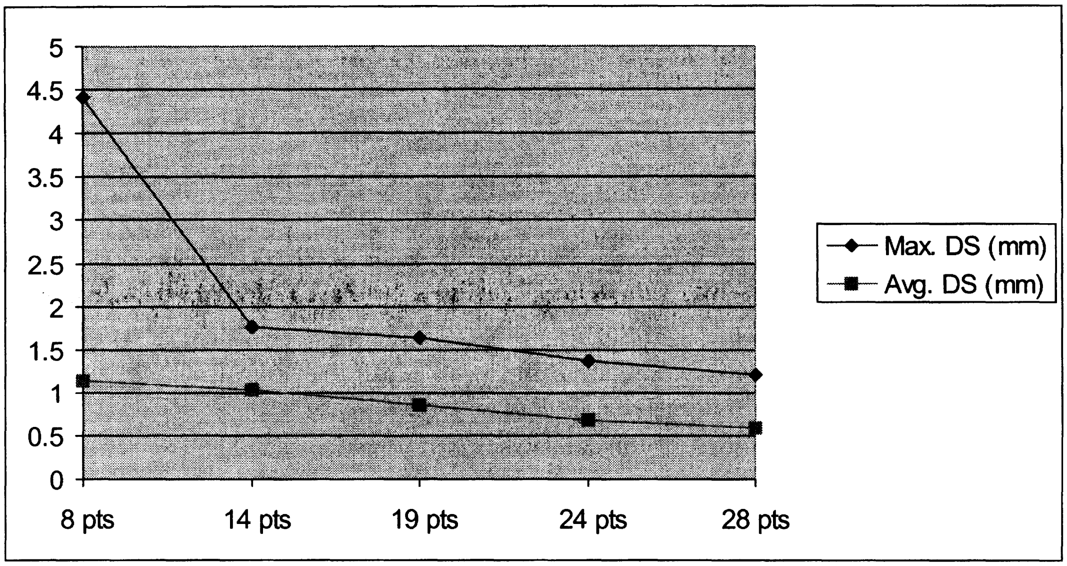


Figure 3.2 Maximum and average distance discrepancies vs. number of well distributed control points

3.1.2 Control Frame Simulations

3.1.2.1 Control Frame Concept

Control frame is a specific strategy of control employed in close range photogrammetric applications. A control frame is usually a strong and portable structure the size and shape of which are especially designed to provide control for certain measuring objects. A set of target points in sufficient number and proper distribution in 3-D space is marked on the control frame, with the 3-D coordinates of all target points in a arbitrary coordinate system precisely determined before the frame is used for photogrammetric measurements. The pattern, size and contrast of the target point marks should be well defined for identifying and measuring on the photographs. The control frame is placed into the object space and photographed together with the measuring object, or alternatively the measuring object could be put into the space of the control frame and photographed in the same way. The target points on the control frame then serve as control points in common sense for further photogrammetric data processing.

3.1.2.2 Patterns of Control Frame Tested

When utilizing control frames in close range applications, it is generally impractical to get uniformly distributed control points in between the unknown points, as is the case of topographic control. Instead, the set of control points on the control frame and the set of unknown points on the measuring object each takes a different range in the object space. Such control configuration is apparently not as geometrically strong as the scattered and well distributed control, but when such choice has to be made, it is worthwhile to know which control frame pattern one should choose. Three commonly used control patterns were tested in this project:

- **a.** control points on the frame are surrounding the unknown points (Figure 3.3 a);
- **b.** control points on the frame are on side of the unknown points (Figure 3.3 b);
- **c.** control points on the frame are semi-surrounding the unknown points (capitalized L pattern – Figure 3.3 c).

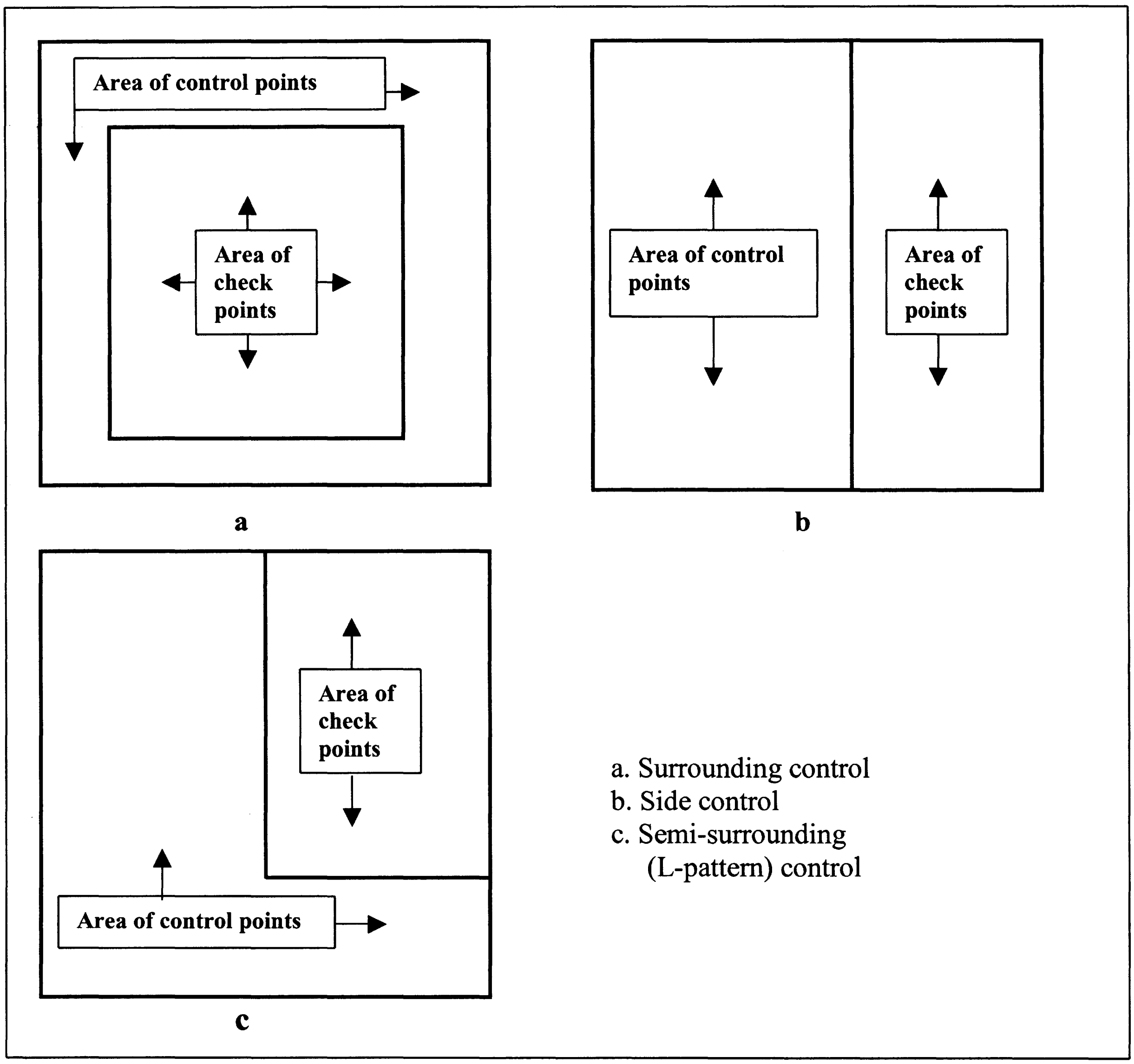


Figure 3.3 Three simulated control frame patterns

3.1.2.3 Results Achieved

For cases a and b above, 8 and 11 simulated frame control points were adopted in each case, and 11 control points were adopted in case c. The simulation was made by specifying the target points in the appropriate area of the plate model as control points and part of the other target points in the other appropriate area as unknown points as shown in Figure 3.3. Keeping in mind that the number of control points in practical applications is often limited, a small number of control points (8 and 11) were used to check the practical accuracy. Table 3.4 shows the coordinate accuracy resulting from 5 different cases (each of pattern a and b above has 2 cases with 8 and 11 control points). The 21 unknown points (check points) used in cases 1 and 2 were kept the same, and also the 22 unknown points (check points) used in cases 3 and 4. The distance accuracies obtained from each of these five cases are shown in Table 3.5.

Table 3.4 Check point accuracy of 5 control frame patterns

Control frame pattern	Case	Number of points		RMS (mm)				Max. discrepancy (mm)		
		Control points	Check points	X	Y	Z	3-D	DX/pt	DY/pt	DZ/pt
Surrounding control	1	8	21	0.77	3.37	5.20	6.24	1.01/302	5.42/302	10.10/402
	2	11	21	0.56	0.59	0.75	1.11	0.83/23	1.24/402	1.36/203
Side control	3	8	22	4.09	0.58	0.70	4.19	5.09/305	1.38/105	1.90/505
	4	11	22	3.38	0.65	0.67	3.51	4.34/305	1.71/105	1.78/505
L-pattern control	5	11	19	1.07	0.33	0.40	1.19	1.70/105	0.83/105	0.89/305

Table 3.5 Distance accuracy of 5 control frame patterns

Control frame patterns	Case	Number of points		Number of distances	Average distance (cm)	Distance error					
						Discrepancy (cm)			Relative error		
		Control points	Check points			Max.	Min.	Avg.	Max.	Min.	Avg.
Surrounding control	1	8	21	10	8.941	0.385	0.009	0.1242	1/23	1/997	1/332
	2	11	21	10	8.941	0.079	0.007	0.0481	1/114	1/1266	1/313
Side control	3	8	22	10	10.507	0.160	0.031	0.0950	1/58	1/486	1/149
	4	11	22	10	10.507	0.213	0.104	0.1430	1/43	1/145	1/78
L-pattern control	5	11	19	10	10.500	0.072	0.005	0.0412	1/94	1/2416	1/659

3.1.2.4 Analysis of Results

1. Accuracy improvement of the check point coordinates achieved by adding control points: The RMS values of the check point coordinates improved in both the surrounding and the side control frame patterns. When only 3 more control points were added while the same frame patterns were kept, the improvement was especially significant for the surrounding frame pattern – the 3-D RMS was decreased by nearly 6 times!
2. Most precise control frame pattern among the three patterns tested: The highest check point coordinate accuracy was achieved by the surrounding control frame pattern. This can be seen from the comparison of the three patterns with the same number of control points (11 points) in Table 3.4 (case 2, 4 and 5). This is however not true

when the number of control points merely meets the minimum requirement of 8 points.

3. Concerns of the accuracy in different directions: It was noticed that much larger coordinate discrepancies and RMS values resulted in the X coordinates than in Y and Z for the side control frame pattern. Further analysis revealed that the X direction in this test was the side direction. It was found that the control points and the check points in this case were distributed in two separate strip areas extending mainly in Y direction such that the extension in X direction was much smaller than that in Y, as shown in Figure 3-3 b. Such control point configuration led to a rather weak control geometry in X direction (side direction). To improve the control geometry, instead of adding 3 more control points into the same side control point area of case 3 to form case 4, the other 3 control points were added in the lower right edge area of the plate model to form the L-pattern control of case 5 as shown in Figure 3-3 c, the accuracy in X direction and the overall accuracy were immediately improved efficiently, as can be seen from the last row in Table 3.4. The semi-surrounding control frame pattern (L-pattern) is therefore worthwhile to be recommended to practical applications in designing control frames when a full surrounding pattern (Figure 3.3 a) cannot be employed due to limitations of the measuring object. The side control frame pattern is not recommended.

4. For the distance accuracy: The distance accuracies as shown in Table 3.5 generally conform with the above analysis concluded from the point coordinates accuracy, except that an unreasonably low accuracy resulted in case 4 compared with case 3, which again suggested the poor control effect of the side control frame pattern. The

average relative errors of the distances were not representative for the corresponding control frame patterns, while the maximum and the average distance discrepancies served as more reasonable accuracy indicators, as happened in the cases of well distributed control configurations discussed earlier.

The 3-D RMS values of the check points resulting from the tests of 5 different cases of the 3 simulated control frame patterns are illustrated in Figure 3.4. The unit of the RMS values represented by the vertical axis in Figure 3.4 is mm, and the vertical axis represents the number of control points used in adjustment.

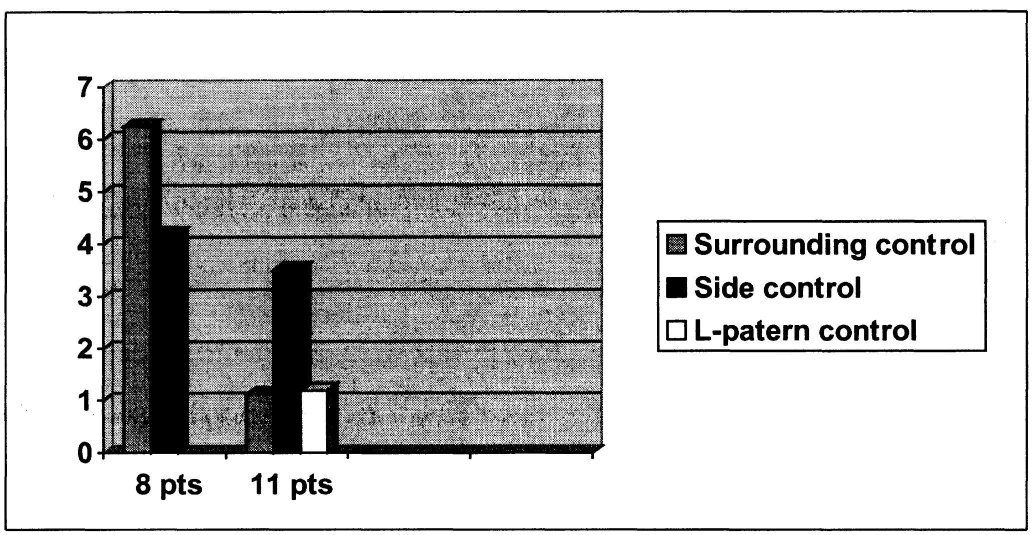


Figure 3.4 3-D RMS of check points in 5 cases of 3 control frame patterns (unit of RMS in mm)

3.2 Differences Between Results from Film Based and Digital Images

3.2.1 Cases Tested and the Results

The evaluation results presented so far were all obtained using images scanned from hard copies. The original images were in the 3 photographs taken with the film based camera Olympus OM 10. In order to investigate the software's performance in processing low cost and low resolution digital camera images and to compare the accuracy obtained by using such digital camera images with that obtained by using scanned hard copy images, the images on the 3 photographs taken with the digital camera Kodak DC-50 were tested, and the results presented in this section. For making the results comparable, 7 different control configuration cases adopted in the test for the scanned hard copy images were selected for the test with the digital camera images. The control and check point configurations in each of the 7 cases were kept unchanged. Table 3.6 shows the 7 cases tested and the check point accuracy resulting from the tests. The distance accuracy is shown in Table 3.7. The first 4 cases in both Table 3.6 and 3.7 are the well distributed control configurations and the last 3 cases are the simulated control frames. The test for the minimum number of control points resulted in the same requirements as stated in Section 3.1.1.1, namely 8 control points for each adjustment project and 7 control points for each photo.

Table 3.6 Check point accuracy for Kodak DC-50 images

Case	Number of points		RMS (mm)				Max. discrepancy (mm)		
	Control pt	check pt	X	Y	Z	3-D	DX/pt	DY/pt	DZ/pt
1	8 well-dis.	53	0.20	0.22	0.26	0.39	0.57/505	0.49/505	0.77/505
2	14 well-dis.	47	0.15	0.24	0.22	0.35	0.34/305	0.77/66	0.66/505
3	24 well-dis.	37	0.16	0.21	0.19	0.32	0.38/53	0.45/203	0.37/65
4	28 well-dis.	33	0.16	0.14	0.17	0.27	0.35/305	0.39/505	0.41/12
5	11 side	22	0.61	0.22	0.23	0.68	0.88/505	0.56/505	0.50/65
6	11L-pattern	19	0.16	0.14	0.29	0.36	0.35/304	0.26/204	0.62/16
7	11 surrd.	21	0.18	0.20	0.13	0.30	0.40/53	0.45/303	0.21/402

Table 3.7 Distance accuracy for Kodak DC-50 images

Case	Number of points		Number of distances	Average distance (cm)	Distance error					
					Discrepancy (cm)			Relative error		
	Control points	check points			Max.	Min.	Avg.	Max.	Min.	Avg.
1	8 w-dis.	53	10	13.400	0.072	0.003	0.029	1/195	1/4995	1/1157
2	14 w-dis.	47	10	13.569	0.044	0.006	0.021	1/341	1/2496	1/826
3	24 w-dis.	37	10	12.901	0.048	0.005	0.019	1/313	1/2997	1/1254
4	28 w-dis.	33	10	13.137	0.052	0.002	0.020	1/217	1/7506	1/1635
5	11 side	22	10	10.507	0.101	0.022	0.051	1/119	1/435	1/248
6	11 L-ptn.	19	10	10.500	0.055	0.005	0.029	1/239	1/2415	1/619
7	11 surrd.	21	10	8.941	0.029	0.002	0.013	1/310	1/4250	1/1294

3.2.2 Analysis of Results

1. The general accuracy obtained by using the digital camera images is significantly higher than that obtained when using the scanned hard copy images for all of the

cases tested. This conclusion is true for each individual case and for the overall accuracy. This is an encouraging conclusion for using digital cameras (which are acquiring a fast growing market) in close range photogrammetry. It is worthwhile to mention that the resolutions of the particular digital camera images (387 by 312, 395 by 316 and 381 by 385 pixels for the 3 photos respectively) is much poorer than that of the scanned hard copy images (1170 by 1170 pixels per photo for each of the 3 photos), such that the point marking (equivalent to conventional photo coordinate measuring) on the digital camera images was apparently more difficult if not necessarily less accurate than on the scanned hard copy images. A similar but less significant accuracy difference was reported by Faig et. al. (1996). The reasons for this difference are still to be investigated. Generally speaking, the low accuracies of the scanned hard copy images are mainly due to the influences of the systematic image errors caused by scanning. Figure 3.5 shows the check point accuracy of the 7 cases obtained from both the scanned hard copy images and the digital camera images.

2. Accuracy improvements achieved by increasing the number of control points shows a similar tendency to that in the corresponding cases using the scanned hard copy images, while the effect is much less significant (the corresponding slope in Figure 3.5 is much flatter). A satisfactory accuracy can be obtained from the digital camera images even with the minimum number of well-distributed control points! The insensitivity of the digital camera images to the number of control points is also expected to be investigated in another project.

3. The poor accuracy areas are the same as in Section 3.1.1.2: mostly in the corner and edge areas.
4. The same conclusions about the most precise control frame pattern and the accuracy in different directions as have been drawn in Section 3.1.2.4 can also be drawn for the digital camera images.
5. Distance accuracy: Figure 3.6 shows a comparison between the distance accuracy obtained by using the digital camera images and that obtained by using the scanned hard copy images for the same control and check point configuration cases. A significantly higher accuracy can again be seen for the cases using the digital camera images.

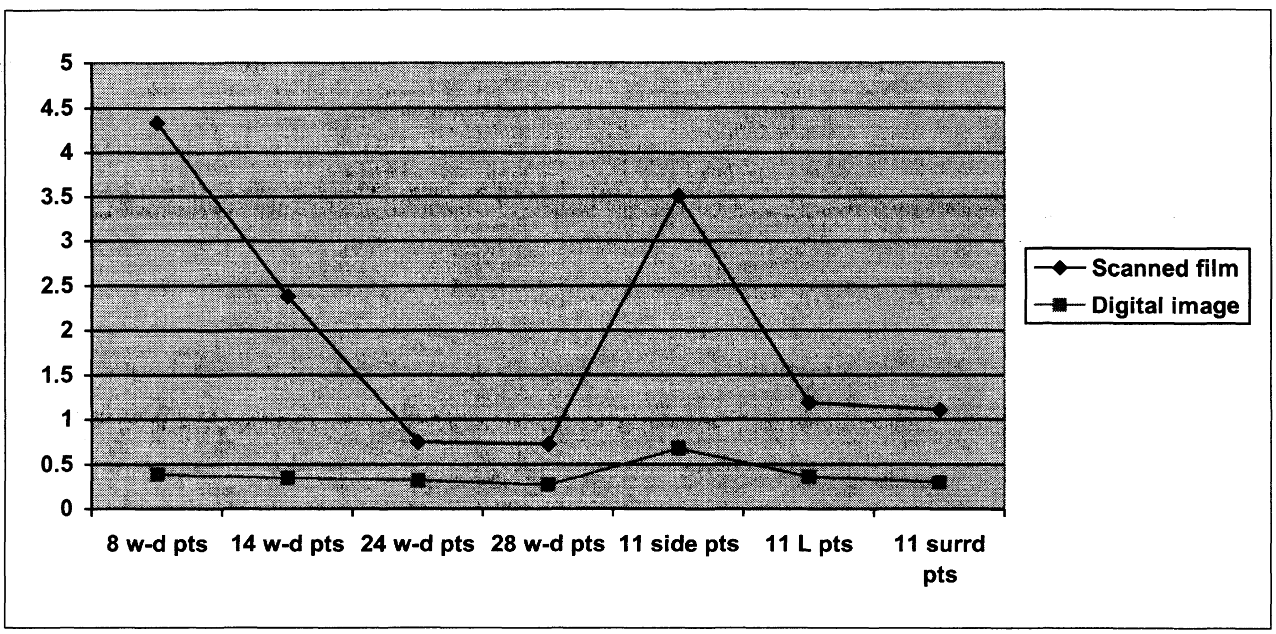


Figure 3.5 Check point 3-D RMS (in mm) comparison between results from scanned hard copy images and from digital camera images in 7 control configuration cases.

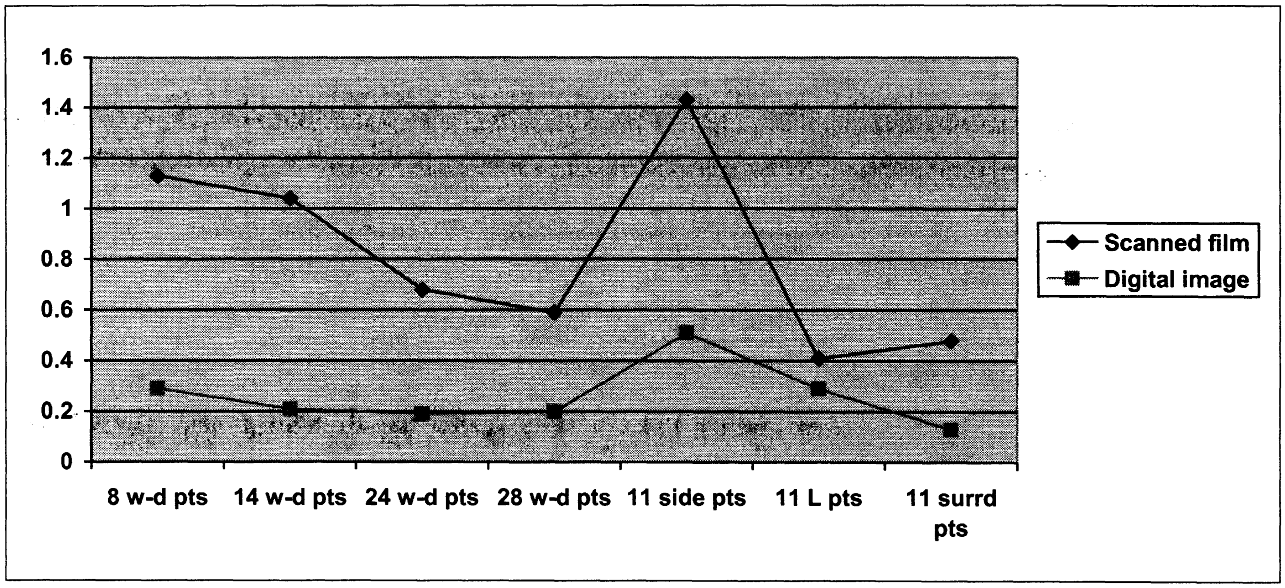


Figure 3.6 Average distance discrepancy (in mm) comparison between results from scanned hard copy images and from digital camera images in 7 control configuration cases.

3.3 Self Calibration

For analytical processing of non-metric images, the significant systematic errors of image coordinates mainly caused by lens distortions, recording medium deformations and imperfections of photo coordinate measuring devices (length errors and non-perpendicularity of the comparator axises) have been considered to be the most influential disadvantage. It was not until the analytical compensations for such systematic photo coordinate errors were achieved successfully during the last two decades or so, that the applications of non-metric images gained popular adoptions in close range photogrammetry.

An option of self-calibration is provided in the PM Pro. in addition to a separate camera calibration program called Camera Calibrator in the software package. It is recommended in the User Manual of the software that this option be chosen when dealing with images taken by non-calibrated cameras. For film based cameras with no fiducial marks input to the program, the program assigns each photograph to an individual camera, which implies the so called photo-variant approach in which each photograph has a set of its own camera parameters in adjustment (Moniwa, 1977). This is the appropriate way of dealing with non-metric images due to the instabilities of the interior orientation parameters of such images between different exposures. On the other hand, for cameras other than the film based ones, the PM Pro's default is: one camera (one set of interior and exterior orientation parameters) for all photographs taken by it, even when the camera is a non-calibrated non-metric one and has no fiducial marks. Since the photographs used in this project were taken at different time periods and it was not practical to obtain the camera calibration parameters, it would be more properly to employ the photo-variant approach for self-calibration or on-the–job calibration when dealing with the non-metric images. The self calibration option was therefore chosen and the photo-variant approach was adopted for all cases tested in the project. For the digital camera images, the software's default option mentioned above was not followed, instead each photograph was manually assigned an individual camera with its own interior orientation parameters.

To investigate the resulting quality obtained by following the software's default (not using the photo-variant approach), three cases of the well-distributed control configurations with the images taken with the digital camera Kodak DC-50 tested in the previous section were tested using the software's default option (one camera for all of the 3 photos). The interior orientation parameters and the lens distortion coefficients obtained by using and not using the photo-variant approach are listed in Table 3.8, where f, x and y are the calibrated principal distance (named focal length in PM Pro) and the photo coordinates of the principal point respectively, K_1, K_2 and P_1, P_2 are the well known polynomial coefficients for the radial lens distortion and the decentering lens distortion respectively. The formulas adopted by PM Pro for radial lens distortions and for decentering lens distortions are Equation (3-1), (3-2) and (3-3) as the following (EOS, 1997).

For any image point (x,y), assuming the principal point is (0,0), the x and y components of image coordinate corrections for radial lens distortions are drx and dry and for decentering lens distortions are dpx and dpy, as shown below.

$$\begin{aligned} drx &= x(K_1 r^2 + K_2 r^4) \\ dry &= y(K_1 r^2 + K_2 r^4) \end{aligned} \qquad (3\text{-}1)$$

where $r^2 = x^2 + y^2$ (3-2)

$$\begin{aligned} dpx &= p_1(r^2 + 2x^2) + 2p_2 xy \\ dpy &= p_2(r^2 + 2y^2) + 2p_1 xy \end{aligned} \qquad (3\text{-}3)$$

The above formulas take into account the most significant components of the conventional geometric calibration. For digital images, there exists another need of radiometric calibration in addition to the geometric calibration, but usually only geometric calibration is included in close range photogrammetric applications, because the geometry of a camera or sensor is of much more significance to maintain the metric accuracy (Shortis, 1996).

Table 3.8 Interior orientation parameters and lens distortion coefficients obtained by using and not using photo-variant approach

Cases		Photo 1		Photo 2		Photo 3	
		Pho-var.	No pho-var.	Pho-var.	No pho-var.	Pho-var.	No pho-var.
Case 1. 8 control points 53 check points	f(mm)	16.051	20.172	16.127	20.172	16.737	20.172
	x(mm)	2.784	2.800	2.784	2.800	2.791	2.800
	y(mm)	2.099	2.100	2.099	2.100	2.100	2.100
	K_1	2.54E-5	3.28E-5	4.37E-6	3.28E-5	1.02E-5	3.28E-5
	K_2	1.79E-4	2.64E-4	4.09E-5	2.64E-4	8.18E-5	2.64E-4
	P_1	-4.98E-8	3.76E-8	-3.90E-7	3.76E-8	-1.21E-7	3.76E-8
	P_2	4.25E-7	3.23E-7	3.50E-7	3.23E-7	-6.30E-7	3.23E-7
Case 2. 24 control points 37 check points	f(mm)	14.255	14.160	15.751	14.160	16.485	14.160
	x(mm)	2.726	2.672	2.765	2.672	2.766	2.672
	y(mm)	2.086	2.079	2.095	2.079	2.098	2.079
	K_1	3.19E-5	-3.29E-5	1.06E-5	-3.29E-5	6.55E-6	-3.29E-5
	K_2	2.17E-4	1.13E- 4	8.76E-5	1.13E- 4	7.95E-5	1.13E- 4
	P_1	-5.68E-7	-3.69E-6	-7.24E-7	-3.69E-6	-1.96E-7	-3.69E-6
	P_2	5.06E-7	1.43E-6	1.67E-7	1.43E-6	-1.68E-7	1.43E-6
Case 3. 28 control points 33 check points	f(mm)	13.988	13.886	15.751	13.886	16.477	13.886
	x(mm)	2.714	2.664	2.765	2.664	2.771	2.664
	y(mm)	2.088	2.086	2.095	2.086	2.101	2.086
	K_1	2.93E-5	-2.55E-5	1.05E-5	-2.55E-5	3.31E-6	-2.55E-5
	K_2	2.05E- 4	1.87E- 4	8.76E-5	1.87E- 4	4.28E-5	1.87E- 4
	P_1	-7.83-E7	-4.05E-6	-7.24E-7	-4.05E-6	-1.34E-7	-4.05E-6
	P_2	3.36-E7	6.90E-7	1.67E-7	6.90E-7	-4.87E-8	6.90E-7

The interior orientation parameters for each photo were found to be different in Table 3.8. The check point RMS comparison between the results of using and not using the photo-variant approach is shown in Table 3.9. The resulting object space coordinates in case 1 of Table 3.9 are in fact erroneous, according to the large coordinate discrepancies which are out of the range of errors but have fallen into the range of mistakes, although the screen display showed "3-D processing was successful" after the adjustment converged, which again indicated that the program would run when a minimum of 8 control points are provided. When the number of control points were increased to 24 or even 28, the object space coordinates with very low precision and very large errors were obtained when the photo-variant approach was not employed, while when this approach was employed on the other hand, very good accuracy was obtained even with the minimum number of control points. In other words, the accuracy of the object space coordinates of the unknown points solved by the software is not sensitive to the number of control points when the photo-variant approach is employed and the self-calibration option of the software is taken. The importance and necessity of employing the photo-variant approach can be clearly seen from the results in Table 3.8 and Table 3.9, which suggests an improvement or correction of the software's corresponding default option.

Table 3.9 Check point RMS obtained by using and not using photo-variant approach

Cases	With photo-variant or not	RMS (mm)				Max. discrepancy/pt. ID		
		X	Y	Z	3D	DX/pt	DY/pt	DZ/pt
1. 8 cntrl pts 53 chk pts	Photo-var.	0.20	0.22	0.26	0.39	0.57/505	0.49/505	0.77/505
	No Photo-var.	41.86	29.09	32.98	60.71	71.33/16	55.19/505	57.43/62
2. 24 cntrl pts 37 chk pts	Photo-var.	0.16	0.21	0.19	0.32	0.38/53	0.45/203	0.37/65
	No Photo-var.	2.00	8.17	6.41	10.57	5.74/305	15.13/305	11.95/305
3. 28 cntrl pts 33 chk pts	Photo-var.	0.16	0.14	0.17	0.27	0.35/305	0.39/505	0.41/12
	No Photo-var.	2.38	8.83	7.01	11.53	6.15/305	16.72/305	13.36/305

Uncertainties of the resulting interior orientation parameters and lens distortion coefficients could be seen from the different cases in Table 3.8 and were also experienced in the other tests. The reasons for the uncertainties are still to be investigated and explained.

Chapter 4 Large Test Field Evaluation

Architectural and industrial objects are among the typical applications for close range photogrammetric measurements. The purpose of this part of the project was to investigate the software's photogrammetric performance for measuring such objects with low resolution, non-metric images, and also to find out the practically appropriate ways for the related applications. The house introduced in Section 2.1 was used as the test object. The images used were five photographs taken with the digital camera Fujix DS-100 as introduced in Section 2.2.

4.1 Different Control Configurations and Corresponding Accuracies

4.1.1 Test Cases and Results

Four different control configurations were tested, which could be classified into two categories:

1. Well distributed control: The 3-D control points were uniformly distributed in object space. This is the traditional and ideal configuration of control. In order to determine the range of accuracies obtainable, and also to verify the conclusion from Section 3.2.2 that the accuracy of the calculated object space coordinates is not sensitive to the number of well distributed control points when photo-variant approach is employed with the self-calibration option for digital camera images, two

configurations with practically the maximum and the minimum numbers of control points respectively were designed and tested:

- a. Configuration with maximum number of control points: A total of 27 point targets uniformly distributed on the four walls were used as control points and the remaining 22 targets as check points. Among the 5 photos used for the adjustment, the minimum number of control points on one photo was 13 and the minimum number of check points on one photo was 12.
- b. Configuration with minimum number of control points: Each photograph contained 7 uniformly distributed control points, which is the minimum number of control points on one photo required by the software. Due to incomplete overlaps of the 5 photos, the total number of control points was 14. The remaining 35 targets were treated as check points.

2. Small area control: In architectural applications, high efficiency is often required allowing for lower accuracy. It is practical under this circumstance that the control could be accomplished quickly by direct and simple measurement in a small area of the object. For instance, a vertical corner line formed by the intersection of two vertical walls could be specified as the Z axis of a local object space coordinate system, and two horizontal lines joining at this Z axis could be specified as the X and Y axis respectively, thus a local object space coordinate system is established. It is then very easy to mark and measure a number of target points (10 to 15 points for example) to the nearest centimetres in this coordinate system with a simple tape. The targets are then recorded on the images of the photos taken and used as control points. This method of providing control points is easy and fast while the geometry and the

inherent accuracy of the control are at a relatively poor level. It is therefore worthwhile to investigate what accuracy can be obtained. Two different small area control configurations were designed and tested:

- c. Lower corner control: A total of 9 targets near the bottom areas of wall 1 and wall 2 were used as control points (point IDs: 141, 142, 231, 232, 233, 241, 242, 243 and 244, see Figure 1.4). The other 40 points were treated as check points. Photo 5 was not used in the adjustment because only two control points had images on it, thus only 4 photos were used in the adjustment.
- d. Lower central control: A total of 9 targets near the bottom areas of wall 2 and wall 3 were used as control points (point IDs: 232, 233, 234, 241, 242, 243, 244, 341, 342 and 343, see Figure 1.4). The other 40 points were treated as check points. Photo 5 was also not used in this adjustment due to insufficient number of control points on it.

The adjustments with 5 photos for the two cases of small area control configurations were also tested, where photo 5 was added to each of the adjustments after the first adjustment with the other 4 photos had converged. The results were omitted because no obvious improvements of the accuracy were obtained.

Table 4.1 shows the number of control and check points on each photo for the above four control configurations. Table 4.2 shows the 3-D RMS values for the check points obtained from the four cases. The distance accuracies of these four cases are shown in Table 4.3.

Table 4.1 Numbers of control and check points in 4 cases of the architectural object

Cases	Photo	Number of points			Notes
		control pts	check pts	total pts	
a. Max. number of well-distributed control points	Photo 1	14	11	25	
	Photo 2	23	19	42	
	Photo 3	27	22	49	
	Photo 4	22	18	40	
	Photo 5	13	11	24	
b. Min. number of well-distributed control points	Photo 1	7	17	24	
	Photo 2	7	28	35	
	Photo 3	7	35	42	
	Photo 4	7	30	37	
	Photo 5	7	18	25	
c. Small area control: Lower corner	Photo 1	7	18	25	Range of 9 control points near left lower corner of the 4 walls
	Photo 2	7	36	43	
	Photo 3	9	40	49	
	Photo 4	9	41	40	
d. Small area control: Lower central	Photo 1	7	18	25	Range of 9 control points near central bottom area of the 4 walls
	Photo 2	9	32	41	
	Photo 3	9	40	49	
	Photo 4	9	31	40	

Table 4.2 RMS of check points in 4 cases of the architectural object

Cases	Number of points		RMS (cm)				Max. discrepancies (cm)		
	control pts	check pts	X	Y	Z	3D	DX/pt	DY/pt	DZ/pt
a	27 well-dis.	22	0.93	0.76	0.48	1.29	1.66/323	1.28/122	1.15/432
b	14 well-dis.	35	1.03	0.87	0.65	1.50	2.34/231	1.85/241	1.64/111
c	9 lower corner	40	4.38	7.86	2.92	9.46	16.50/413	14.75/442	7.98/412
d	9 lower central	40	3.32	7.23	3.03	8.51	7.32/111	15.72/442	8.48/411

Table 4.3 Distance accuracy from 4 cases of the architectural object

Cases	Number of points		Number of distances	Average distance (cm)	Distance error					
					Discrepancies (cm)			Relative errors		
	control points	check points			Max.	Min.	Avg.	Max.	Min.	Avg.
a	27	22	10	393.579	1.65	0.070	0.64	1/197	1/10127	1/1684
b	14	35	10	358.675	2.99	0.45	1.10	1/78	1/1223	1/440
c	9	40	10	392.311	11.18	0.18	4.64	1/37	1/1337	1/310
d	9	40	10	434.092	9.85	0.063	4.45	1/41	1/13103	1/1402

4.1.2 Analysis of Results

1. Accuracy improvements achieved by increasing the number of well distributed control points: Increasing the number of well distributed control points improved the accuracy, but the accuracy improvement of the check point coordinates was not significant. In other words, the accuracy of the check points was not sensitive to the number of well distributed control points. This conclusion is the same as in Section 3.2.2.
2. Accuracy of the small area control configurations: The check point object space coordinate accuracy and the distance accuracy obtained from both of the two small area control configurations were significantly poorer than those obtained form the well distributed control configurations. The average factors were 6.4 times for the 3-D RMS and 5.2 times for the average distance discrepancies respectively. Such accuracy is normally not acceptable, therefore these small area control configurations cannot be recommended to practical applications. The reasons for the low accuracy

lie in the very weak geometry of the control point distributions, because all control points are limited to a very small range of the object space and of each photo. Such control configuration is even much weaker than that of the side by side control frame pattern discussed in Section 3.1.2, where the control points are distributed on one side of the object space and cover approximately half of the object space. It is hence not surprising that the accuracy of the small area control configurations is very poor knowing that the side by side control frame pattern has the lowest accuracy among the control patterns discussed in Section 3.1.2. The areas with the poorest accuracy in the small area control configurations were naturally found in the areas far away from the control points. This is evident from the point identification numbers with maximum discrepancies of the object space coordinates.

3. A recommendation for convenient control for architectural objects: When the design documents of a architectural object are available, the proper corner points and points on some vertical and horizontal wall edges can be chosen as control points. The designed distances between these points along each of the wall edges can be transformed into coordinate values in a local object space coordinate system defined by the user according to the structure of the particular object. Satisfactory control can be expected when the selected control points are well distributed or are surrounding the object. Point targeting and field checking of the major design distances are necessary for this strategy.
4. Range of accuracies: The range of accuracies was derived from the results from the two cases of well distributed control configurations, because the small area control cases were not practically acceptable. For the accuracy of the object space

coordinates of unknown points, a coordinate RMS of less than 1.0 cm was achieved, with the maximum coordinate discrepancy being less than 2.3 cm. For the distance accuracy, an average discrepancy of less than 1.1 cm was achieved, with a maximum discrepancy of less than 3.0 cm. The average relative distance accuracy of 1/1684 for case a' matches the one reported 1/1700 by Klaus Hanke (1998), obtained in a project sponsored by EOS System Inc. Both the object space coordinate accuracy and the distance accuracy are practically acceptable to general engineering applications. It was noticed that more significant improvements for the distance accuracy occurred when increasing the number of well distributed control points than for the object space coordinate accuracy.

Figure 4.1 shows the object space 3-D RMS values for the check points from the four cases. Figure 4.2 shows the maximum and average discrepancies of the distances obtained from the four cases.

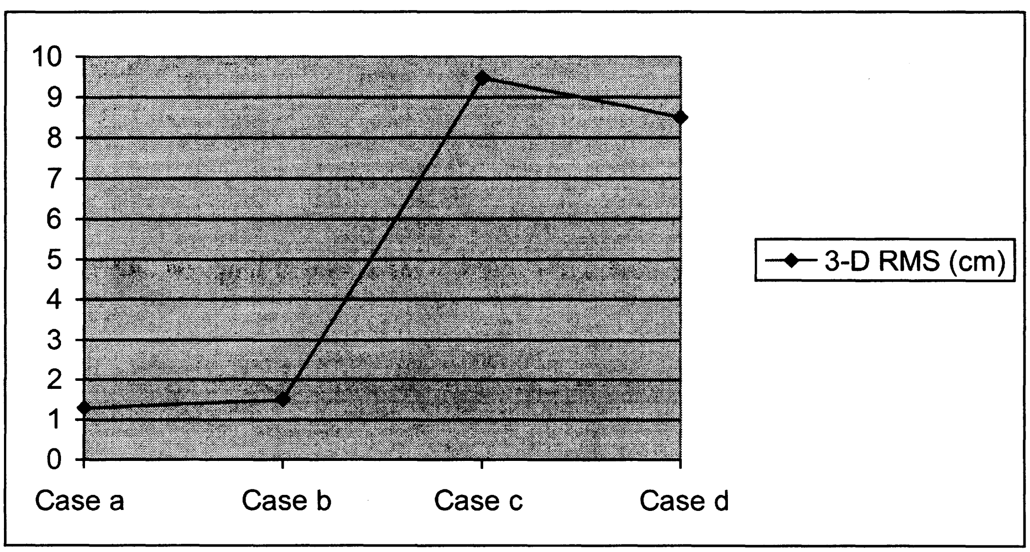


Figure 4.1 Check point 3-D RMS from 4 cases of the architectural object
(See Table 4.1 for case descriptions)

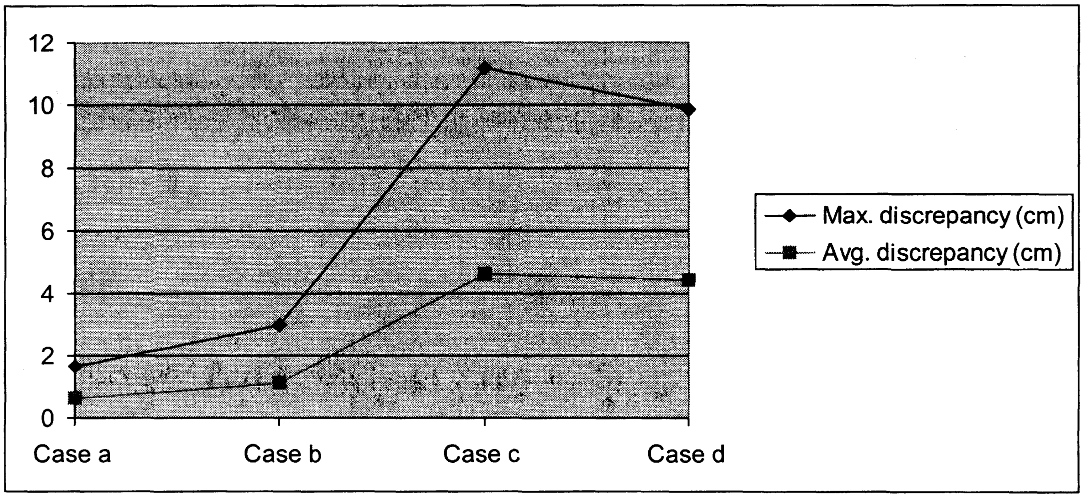


Figure 4.2 Maximum and average discrepancies of distances from 4 cases of the architectural object (See Table 4.1 for case descriptions)

4.2 Self Calibration

In the adjustment for each of the 4 cases of the architectural object, the option of Self Calibration provided by the software was selected with the photo-variant approach as described in Section 3.3, i.e. each photograph in each adjustment was manually assigned an individual camera with its own interior orientation parameters. A noticeable fact was found from the adjustment results, namely that the lens distortion coefficients K_1, K_2, P_1 and P_2 for each of the four cases were all zeroes, in other words these four coefficients were not solved in the adjustments, eventhough the same operational steps were followed as adopted in the tests in Section 3.3 where these coefficients were solved. The failure of solving for the lens distortion coefficients is still to be explained. Table 4.4 shows the interior orientation parameters obtained from the four cases of the house object.

Table 4.4 Interior orientation parameters and lens distortion coefficients from 4 cases of the architectural object

Cases	Parameters	Photo 1	Photo 2	Photo 3	Photo 4	Photo 5
a. 27 well-distributed control points 22 check points	f (mm)	7.199	7.247	7.717	7.428	7.320`
	x (mm)	2.782	2.696	2.760	2.895	2.966
	y (mm)	2.077	2.140	2.170	2.103	2.075
	K_1	0	0	0	0	0
	K_2	0	0	0	0	0
	P_1	0	0	0	0	0
	P_2	0	0	0	0	0
b. 14 well-distributed control points 35 check points	f (mm)	7.271	7.426	7.656	7.617	7.375
	x (mm)	2.912	2.898	2.763	2.849	2.778
	y (mm)	2.116	2.127	2.103	2.076	2.115
	K_1	0	0	0	0	0
	K_2	0	0	0	0	0
	P_1	0	0	0	0	0
	P_2	0	0	0	0	0
c. 9 left lower small area control points 40 check points	f (mm)	8.243	8.333	8.425	7.634	
	x (mm)	2.739	2.827	2.833	2.874	
	y (mm)	1.997	2.092	2.137	2.183	
	K_1	0	0	0	0	
	K_2	0	0	0	0	
	P_1	0	0	0	0	
	P_2	0	0	0	0	
d. 9 central lower small area control points 40 check points	f (mm)	8.423	8.427	8.125	7.218	
	x (mm)	2.800	2.767	2.806	2.793	
	y (mm)	2.098	2.162	2.102	2.118	
	K_1	0	0	0	0	
	K_2	0	0	0	0	
	P_1	0	0	0	0	
	P_2	0	0	0	0	

The interior orientation parameters for different photos turned out to be different in each case in Table 4.4, which implies the necessity of employing the photo-variant approach. The differences in the same parameters for the same photograph between different cases on the other hand, indicated the uncertainties of the software for solving for the interior orientation parameters, which is improper in general photogrammetric theory. The principal distance and the photo coordinates of the principal point of the same photograph should keep unchanged for different adjustment cases. One reason for the slight changes of the principal point coordinates may lie in the fact that the photo points were marked independently on each photo in each case, which is equivalent to an independent photo coordinate measurement for each individual photo in each adjustment case. Different photo coordinates of the principal point would occur in different cases if the photo coordinate systems defined by the software for the same photo in different adjustment cases were not completely coincident. However, for the principal distance, the same value should be kept for the same photo in different cases. A need of improvement is felt for the software to solve the problem of the uncertainties and failures in solving the interior orientation parameters and lens distortion coefficients.

Chapter 5 Operational Concerns

The tests and analysis in the previous two chapters have shown that the off-the-shelf digital close range photogrammetric software package PhotoModeler Pro can be flexibly applied to both small and large measuring objects with practically acceptable accuracies, and that the pre-existing non-metric images of both scanned hard copy image type and low-resolution digital camera image type can be utilized for measuring purposes. During the operation of this software however, concerns of different aspects were experienced for obtaining proper results. Some of these concerns were worth to be analyzed, explained or solved theoretically, for others it was felt necessary to be reported as valuable experiences to benefit the users or to serve as references for the related software designers. This chapter is designed to deal with the main concerns.

5.1 Tutorials and Help Tools

To start working with PhotoModeler, a convenient and efficient way is to take advantage of the tutorial animation movies provided by the designer, and follow the projects in the tutorials to get trained. As a helpful characteristic of the software package, the tutorials contain 9 sections and 61 segments; each section contains 4 to 9 segments. With the proper images, data, voice and text explanations, the tutorial movies covered the operation steps for all the main features of the software package and provided an intuitive step by step instruction. The proper steps to make use of the tutorial movies can be recommended as:

a) Go through all of the 9 sections to acquire an outline of the features and operation steps.
b) Repeat the whole set of movies by creating the user's projects using the images and data in the tutorials and following each tutorial project with the user's corresponding project in parallel. For the users concentrating on the specific applications, the tutorial projects of the other types rather than the user's interests may or may not be followed.
c) Go back to the segments where difficulties if any were encountered and solve for the difficulties.
d) Consult the corresponding segments during the user's application projects.

Once the user has started his/her own application projects with PhotoModeler, the tutorial movies can be referenced together with the other help tools, including the User Manual, help menu and Trouble Shooting menu displays in the program. The help tools appear in different operation steps of the software which help marking the identical points, curve lines and cylinders (image correlation help tools) and the setting and measuring of different features of the images and camera stations.

5.2 Input

The input to PhotoModeler Pro includes image input, control point file input and camera input. They are summarized in the following subsections and some of the practical concerns are presented.

5.2.1 Image Input

The images to be input to PhotoModeler must be in digital form, other forms of images (e.g. film-based photographs and video images) should be transformed into digital form before input. The software accepts the following formats of digital images: Targa-TGA, TIFF, GIF, PCX, DCX, BMP, DIB, JPEG, WMF, WPG, PICT, IFF, PhotoShop-PSD and Kodak PhotoCD-PCD. The image input operation is performed under the Photograph Import dialog (for PM Pro ver. 3.0j) or Photo Import Wizard (for PM Pro ver. 3.1).

5.2.2 Camera Input

The camera input is performed in the Camera Information dialog for ver. 3.0j and in the Camera Wizard for ver. 3.1. The input includes camera name, camera type, status of fiducial marks and the values of the camera parameters including focal length (meaning principal distance), format size (image height and width) and the photo coordinates of the principal point. Some of the most common camera types and their parameters are provided by the software as options of defaults.

A noticeable fact is that the interior orientation parameters of the cameras are required as input data in any case. It was experienced that the quality (accuracy) of the result is sensitive to large differences of the input camera parameters, even when there were over twenty 3-D control points.

5.2.3 Control Point File Input

The input of the control point file is performed after the input of images and cameras, and the operation is made under the Control Import dialog of the Control Point mode. In addition to a control point file, a unit of the control coordinates and a precision value are required to be set in this dialog. The average standard deviation of X, Y and Z coordinates of the control points can be used as the precision value. For Version 3.1, an option of fixing the control point coordinates is available, which will make the control point coordinates fixed in the adjustment. One of the following 3 types of control point files can be chosen as the input control point file:

1. 3-D DXF file: Any DXF file from CAD or from PM Pro output, 3-D points and optionally 3-D lines and text strings are contained in the DXF file. The text strings have identical coordinate values to the points in the file.
2. Text control file: A simple ASCII text file in which each line contains the information of one control point, including point ID, 3-D coordinates and precision value from left to right. Version 3.1 allows for 3 precision values for X, Y and Z respectively.
3. Cube: A rectangular cuboid appears in the images with known size of the dimensions. The size of the cuboid needs to be entered and the eight corner points of the cuboid are then recognized by the software as control points. The eight corner points in this case must be well-defined points.

It was experienced that incorrect results were obtained when the same precision value was input in the text control file and the Control Import dialog, but this problem was solved by omitting the precision value in the text control file while remaining it in the Control Import dialog.

5.3 Coordinate Systems

All of the coordinate systems involved in the software were found to be right-handed systems. It needs to be realized that conventional surveys for the control points may provide the control coordinates in a left-handed system, a transformation from left to right handed coordinate system is needed before the control point coordinates can be used in PM Pro under this circumstance.

The 3-D view of the control points available in the software was found to be a useful tool to check whether a left-handed control point coordinate system is directly introduced into the software by a text control file without the necessary transformation. Because the 3-D viewer recognizes all control coordinates in a text control file as the coordinates in a right-handed coordinate system and illustrates these control points in the 3-D viewer, a reversed phase of the control points can easily be found in the 3-D viewer by comparing the 3-D view of the control points with reality.

5.4 Measuring

5.4.1 Photo Coordinate Measuring

The measuring of the photo coordinates is accomplished by marking the image points monoscopically on an open photograph with a pointing cursor called Point Marking Tool. The photo coordinates of the marked photo points do not need to be input into the software separately for adjustment, nor could a separate photo coordinate file be seen formed. The photo coordinates of the selected active point mark are however displayed at the bottom of the screen. The origin of the photo coordinate system is set at the top-left corner of the photograph, the x axis is horizontally left-wards and the y axis is vertically downwards.

The unit of the photo coordinates is in pixels, which implies that the sizes of different pixels in a digital image are considered to be uniform. This assumption of uniform pixels in a digital image was reportedly adopted by a number of research projects such as in Faig *et. al.* (1996). The accuracy of a photo coordinate (photo point marking) is at the sub-pixel level. The values of the photo coordinates shown at the screen bottom are displayed to 0.01 pixel.

It is very helpful to utilize the image enhancement function and the zoom-in/zoom-out function provided by the software to adjust the contrast and brightness of the image and to magnify/reduce the image for best point marking. The image resolution and the point definition were found to be nearly the only influential factors to the accuracy of photo coordinates, because the image could be magnified without limitation provided the resolution allows it.

The marking of the points identical to the marked points can be made with the Referencing Tool, which has the function of point correlating and optionally point marking at the same time. Referencing is the term employed in this software meaning correlating in photogrammetric term. In addition to point correlating, the Referencing Tool has another function of correlating cylinders in different photos.

5.4.2 Feature Measuring in Object Space

The software provides the capability of measuring a series of features in object space, based on the marked points with known object space coordinates (control coordinates or calculated coordinates solved by PM Pro) and the cylinders which have been marked and solved by the software. The features which can be measured include: 3-D coordinates of points, lengths of lines between the points, plane areas of the area elements composed by the enclosed ranges of sets of 3 marked points, diameters and lengths of the marked and solved cylinders. In version 3.1, the camera stations resulted from the adjustments of the software and displayed in the 3-D viewer can be measured like the other marked points except for area measurement.

The measurements are made with the Measurement Tool under the Measure mode. Once the Measurement Tool (a pointing cursor) is clicked on the feature to be measured, the result of the measurement and the information of the feature being measured (feature type, point ID, point coordinate precision values, unit of the measuring value etc.) are displayed in the Measure dialog that is open when the Measure mode is selected. In version 3.0j, all measurements are made on a displayed photograph, while the measurements can be made in the Table Viewer and 3-D Viewer in addition to the displayed photograph in version 3.1.

The capability of measuring the geometrical elements directly on a digital photograph is a very useful and convenient feature of the software for various users, especially for users in the fields other than photogrammetry or geomatics. This feature has also provided the potentials of merging close range photogrammetry with GIS. Digital image data of architectural structures is nowadays contained in many GIS packages, such as CARIS developed by Universal Systems Ltd. Digital image processing is invoked to display the corresponding digital photograph when the photograph is retrieved. It is however a waste of the image data source if the images are stored only for view as in CARIS. With the feature of direct measurement on the digital photograph, as provided by PhotoModeler Pro, the geometrical elements of the architectural object can be measured directly on the displayed photograph according to what the user needs. The firemen would probably need to know immediately the widths and heights of some doors and windows on a house in case of fire for instance. The direct measuring on photograph is apparently more user-friendly than looking up the figures by identifying the right lines and figures in complex engineering drawings, especially for the people who are not familiar with the engineering drawings. It is felt worthwhile to set up another project to investigate and test this merger of digital close range photogrammetry with GIS. Figure 5.1 shows the measurement of a window width on a digital photograph of the wooden house.

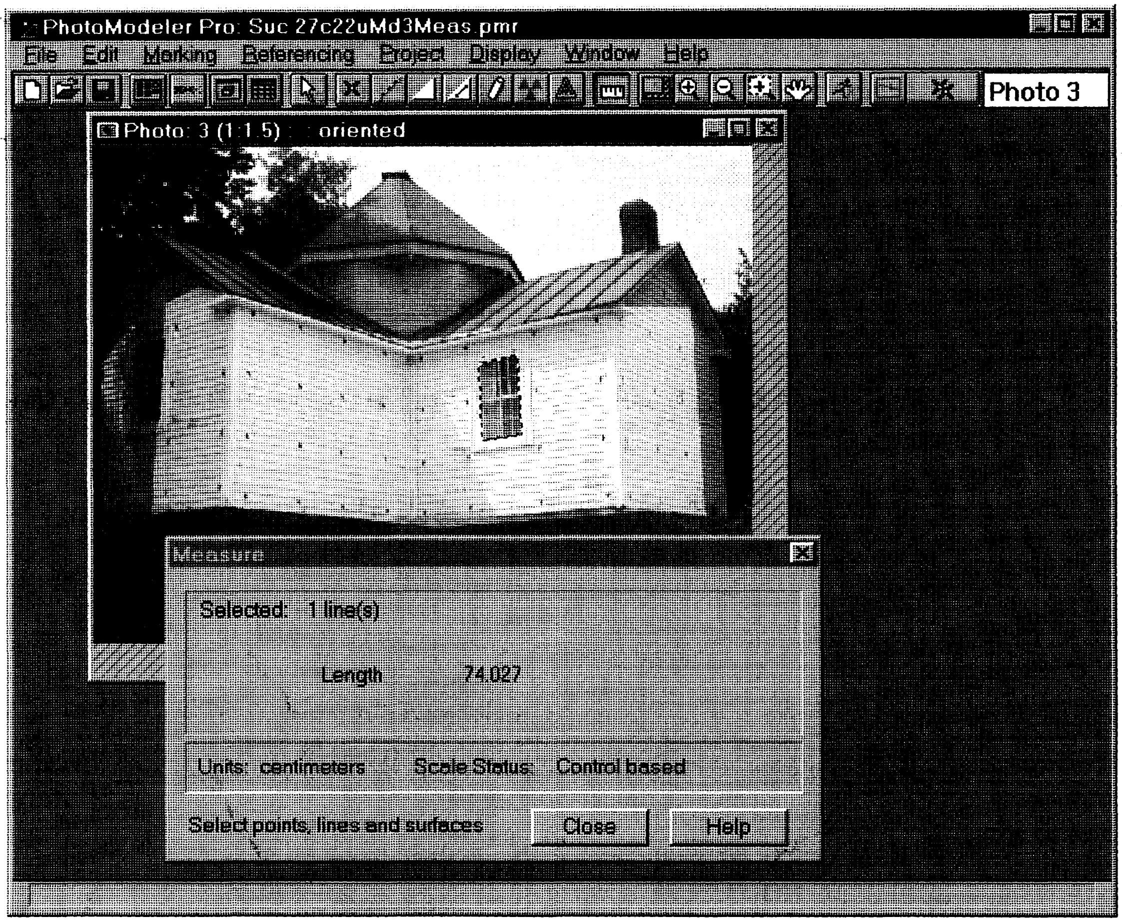


Figure 5.1 Direct measurement of a window width from digital photograph with PM Pro -- potential of merging c-r photogrammetry with GIS

5.5 Repeated Processing

In the tests of over forty different cases of adjustment made with PM Pro, it was found that different results were obtained from each of the repeated processing for the same adjustment project, where processing is a term employed in the User Manual and other related texts of PM Pro meaning the running of the adjustment programs of PM Pro.

The photographs used, control points and unknown points (check points) were all kept unchanged during the progress of the repeated processing for each case. This section is designed to present the effects of the repeated processing on the resulting check point accuracies and camera parameters in each of the different cases. Only part of the representative results from the repeated processing are presented in this Section and the related analysis is summarized, with the other similar results omitted to avoid unnecessary length of this report.

5.5.1 Repeated Processing for Scanned Hard Copy Images

5.5.1.1 Test Cases and Results

The adjustment results of the scanned hard copy images employed for the evaluations in Chapter 3 were all obtained from repeated processing, i.e. repeated adjustment, for each case. The reason for repeating the processing lies in the fact that different results were obtained from each of the repeated processing for the same case and the accuracy of the check points was improved effectively through repeated processing.

Table 5.1 shows the RMS values of the check points obtained from each repeat of the processing for one particular case of the metal plate test object: 14 well distributed control points and 47 check points. The interior and exterior orientation parameters of each camera were modified by the result obtained from each processing.

Table 5.2 shows the exterior and interior orientation parameters resulting from each repeat of the processing for the same case as in Table 5.1. The exterior orientation parameters include the object space coordinates and rotation angles of the cameras; the interior orientation parameters include the principal distance and photo coordinates of the principal point, and the lens distortion coefficients K_1, K_2, P_1 and P_2 obtained.

Table 5.3 shows a comparison of the RMS values of the check points between the results form the first processing (no repetition) and those from the eighth repeated processing for 10 different control configuration cases for the metal plate test object.

Table 5.1 Check point RMS from each repeated processing for the configuration with 14 well distributed control points and 47 check points on the metal plate test object (scanned hard copy images)

Repeat (modification) times	RMS (mm)				Max. discrepancy (mm)		
	X	Y	Z	3D	DX/pt	DY/pt	DZ/pt
Md 1	1.29	2.80	2.18	3.77	3.82/105	6.51/105	4.47/505
Md 2	1.01	1.95	1.76	2.81	3.01/105	4.62/102	3.58/505
Md 3	0.95	1.68	1.65	2.54	2.76/105	3.97/102	3.31/505
Md 4	0.93	1.60	1.63	2.46	2.67/105	3.74/102	3.34/505
Md 5	0.92	1.56	1.62	2.43	2.63/105	3.63/102	3.22/505
Md 6	0.91	1.53	1.61	2.41	2.60/105	3.57/102	3.22/105
Md 7	0.90	1.51	1.61	2.39	2.58/105	3.52/102	3.23/505
Md 8	0.90	1.50	1.61	2.38	2.53/105	3.48/102	3.24/505

Table 5.2 Interior and exterior orientation parameters and lens distortion coefficients from each repeated processing for the same case as in Table 5.1

Repeat times	Photo Number	Camera station coordinates (cm) and rotation angles (degrees)						Interior orientation parameters (mm)			Lens distortion coefficients			
		X	Y	Z	ω	φ	κ	f	x	y	K_1	K_2	P_1	P_2
Md 1	Photo 1	-4.87	-48.23	26.79	60.61	-10.27	-2.30	67.77	18.32	11.23	4.91E-6	2.71E-8	4.02E-6	2.41E-5
	Photo 2	-4.59	-30.17	73.70	2.23	-6.80	-4.41	100.15	18.10	11.16	-6.91E-5	1.76E-7	4.58E-5	5.32E-5
	Photo 3	-5.66	-55.34	-11.09	99.57	-9.58	0.17	76.10	18.42	11.06	-5.50E-5	-1.40E-7	7.90E-7	1.09E-5
Md 2	Photo 1	-5.63	-50.87	28.08	60.81	-10.52	-2.24	71.37	18.29	11.19	9.30E-6	2.80E-8	1.85E-6	4.81E-5
	Photo 2	-4.48	-27.98	60.68	25.91	-8.25	-4.10	82.64	18.06	11.14	-9.16E-6	5.67E-8	5.61E-5	-6.78E-5
	Photo 3	-5.61	-53.06	-9.46	98.24	-10.35	0.20	70.70	18.30	11.05	-6.69E-6	5.52E-8	6.24E-7	1.61E-5
Md 3	Photo 1	-5.73	-50.66	27.89	60.88	10.67	-2.22	71.08	18.28	11.17	1.41E-5	2.03E-8	1.81E-6	5.47E-5
	Photo 2	-4.36	-27.02	56.74	26.72	-8.73	-4.08	77.44	18.05	11.11	9.81E-6	1.97E-8	5.88E-5	-7.01E-5
	Photo 3	-5.67	-52.93	-9.13	97.91	-10.55	0.22	70.01	18.27	11.03	1.52E-5	4.39E-9	1.29E-6	2.42E-5
Md 4	Photo 1	-5.78	-50.64	27.85	60.92	-10.73	-2.21	71.06	18.28	11.16	1.82E-5	1.18E-8	2.52E-6	5.50E-5
	Photo 2	-4.30	-26.56	55.22	27.00	-8.92	.4.07	75.44	18.04	11.08	1.97E-5	-1.44E-11	5.91E-5	-6.93E-5
	Photo 3	-5.70	-52.99	-9.06	97.84	-10.61	0.24	69.98	18.27	11.02	2.45E-5	1.80E-8	2.58E-6	3.29E-5
Md 5	Photo 1	-5.80	-50.68	27.83	60.94	-10.75	-2.21	71.11	18.28	11.16	2.14E-5	4.81E-9	2.70E-6	5.28E-5
	Photo 2	-4.26	-26.28	54.39	27.14	-9.02	-4.07	74.33	18.05	11.05	2.62E-5	-1.32E-8	5.82E-5	-6.80E-5
	Photo 3	-5.73	-53.08	-9.06	97.85	-10.63	0.25	70.10	18.27	11.00	2.96E-5	-3.02E-8	4.26E-5	4.11E-5
Md 6	Photo 1	-5.82	-50.72	27.83	60.97	-10.76	-2.21	71.17	18.28	11.17	2.38E-5	-6.87E-10	3.09E-6	4.98E-5
	Photo 2	-4.22	-26.07	53.81	27.24	-9.09	-4.06	73.56	18.05	11.03	3.09E-5	-2.98E-8	5.69E-5	-6.67E-5
	Photo 3	-5.75	-53.17	-9.08	97.87	-10.64	0.26	70.23	18.27	10.98	3.29E-5	-3.79E-8	6.18E-6	4.87E-5
Md 7	Photo 1	-5.83	-50.78	27.83	61.00	-10.76	-2.20	71.23	18.28	11.17	2.56E-5	-4.92E-9	-3.40E-6	4.66E-5
	Photo 2	-4.19	-25.92	53.36	27.32	-9.16	-4.06	72.96	18.06	11.02	3.46E-5	-3.04E-8	5.50E-5	-6.56E-5
	Photo 3	-5.77	-53.25	-9.11	97.90	-10.64	0.27	70.37	18.27	10.97	3.53E-5	-4.32E-8	8.24E-6	5.54E-5
Md 8	Photo 1	-5.84	-50.83	27.81	61.02	-10.77	-2.20	71.29	18.28	11.18	2.70E-5	-8.17E-9	3.64E-6	4.35E-5
	Photo 2	-4.17	-25.80	53.00	27.38	-9.21	-4.05	72.48	18.07	11.00	3.73E-5	-3.62E-8	5.29E-5	-6.48E-5
	Photo 3	-5.79	-53.32	-9.13	97.93	-10.64	0.28	70.49	18.26	10.95	3.70E-5	-4.71E-8	1.04E-5	6.15E-5

Table 5.3 Check point RMS comparison between first processing results and the eighth repeated processing results from 10 cases of the metal plate test object

Cases	RMS (mm): 1st processing / 8th processing				Max. discrepancy: 1st processing / 8th processing			Note
	X	Y	Z	3D	DX/pt	DY/pt	DZ/pt	
1. 8 well-dis. cntrl. pts 53 check points	1.57 1.06	3.97 2.75	3.56 3.17	5.56 4.33	4.78/505 3.73/105	7.98/505 6.06/105	8.58/505 7.78/505	Well distributed control configurations
2. 14 well-dis. cntrl. pts 47 check points	1.31 0.90	2.87 1.50	2.18 1.61	3.83 2.38	3.98/105 2.53/105	6.65/102 3.48/102	4.38/105 3.24/505	
3. 19 well-dis. cntrl. pts 41 check points	0.63 0.55	1.14 0.91	1.09 0.86	1.70 1.37	1.85/505 1.46/505	2.08/402 1.74/402	2.59/505 1.98/502	
4. 24 well-dis. cntrl. pts 37 check points	0.55 0.45	0.69 0.39	0.62 0.45	1.08 0.75	1.48/305 1.06/305	1.50/101 0.79/402	1.33/505 0.98/101	
5. 28 well-dis. cntrl. pts 33 check points	0.53 0.41	0.69 0.43	0.64 0.43	1.08 0.73	1.53/305 1.08/305	1.49/101 0.81/302	1.48/505 0.98/505	
6. 8 surrd. cntrl. pts 21 check points	0.89 0.77	3.91 3.37	4.55 5.20	6.07 6.24	1.21/23 1.01/302	6.46/302 5.42/302	9.20/402 10.10/402	Control frame simulations
7. 11 surrd. cntrl. pts 21 check points	0.70 0.56	1.20 0.59	1.19 0.75	1.83 1.11	1.00/32 0.83/23	2.11/203 1.24/402	1.96/203 1.36/203	
8. 8 side cntrl. pts 22 check points	4.50 4.09	1.90 0.58	1.39 0.70	5.07 4.19	6.79/505 5.09/305	4.85/105 1.38/105	3.60/505 1.90/505	
9. 11 side cntrl. pts 22 check points	3.52 3.48	0.79 0.65	0.78 0.67	3.69 3.51	4.70/505 4.34/305	2.21/105 1.71/105	1.78/505 0.35/305	
10. 11 L-pattern cntrl. Pts 19 check points	1.11 1.07	0.72 0.33	0.37 0.40	1.38 1.19	2.03/105 1.70/105	1.16/36 0.83/105	0.35/305 0.89/305	

5.5.1.2 Analysis of Results

1. The accuracies of the check points in the 10 cases in Table 5.3 are all generally improved through the repeated processing, in spite of the slight increase of two RMS values for cases 6 and 10 in Z direction. The accuracy improvement is especially significant for the well distributed control configurations. It can therefore be

suggested that repeated processing is generally necessary for processing scanned hard copy images with PM Pro. Figure 5.2 illustrates the improvement of the check point 3-D RMS achieved by repeated processing for the five well distributed control configuration cases (case 1 to 5 in Table 5.3). Figure 5.3 illustrates a comparison of the check point 3-D RMS between the results from the first processing and those from the eighth repeated processing for the five cases of simulated control frame configurations (case 6 to 10 in Table 5.3).

2. For a particular case, taking the well distributed control configuration with 14 control points and 47 check points as the example, the improvement of the check point accuracy becomes insignificant when the repeating times of the processing reaches a certain level (more than 5 or 4 for this example case). However, it remains as a problem for the users to find out whether the processing should be repeated and /or how many repeating times is appropriate for a practical application. Effective checks of the accuracy and indicators for the need of repeating the processing are still needed. It should be mentioned that the program-provided precision values of the object space coordinates for the calculated check points showed essentially no difference between the first processing result and the result from any of the eight repeated processing for each case tested. Figure 5.4 illustrates the improvement of the check point accuracy from each repeated processing for the example case (case 2 in Table 5.3).

3. For the interior and exterior orientation parameters resulting from each repeated processing for the same case, as shown in Table 5.2, the exterior orientation parameters and the photo coordinates of the principal point of the same photo

obtained from the last two processing practically approached the same values, but the results of the principal distance obtained from each processing did not show as good a convergence when compared with the other orientation parameters. In other words, uncertain solutions of the principal distance were obtained from PM Pro in different repeated adjustments for the same case.

4. For the lens distortion coefficients obtained from each of the repeated processing for the same case, as shown in Table 5.2, different results of the same coefficients for the same photograph (i.e. the same camera, considering the photo-variant approach adopted) were obtained from different processing. This indicated the uncertainties of these coefficients obtained from PM Pro. A magnitude comparison of the four coefficients shows: the absolute values of K_2 are generally less than those of K_1 and P_1, P_2 by 2 orders of magnitude, while P_1 and P_2 have the same order of magnitude. This suggests that the symmetrical radial lens distortions and de-centering lens distortions are all significant and therefore should be compensated when scanned hard copy non-metric images are utilized; while the term of K_2 could be neglected compared to the other 3 terms. Karara and Abdel-Aziz (1974) also stressed the significance of the terms of K_1 for the lens distortions in non-metric cameras based on a series of accuracy tests.

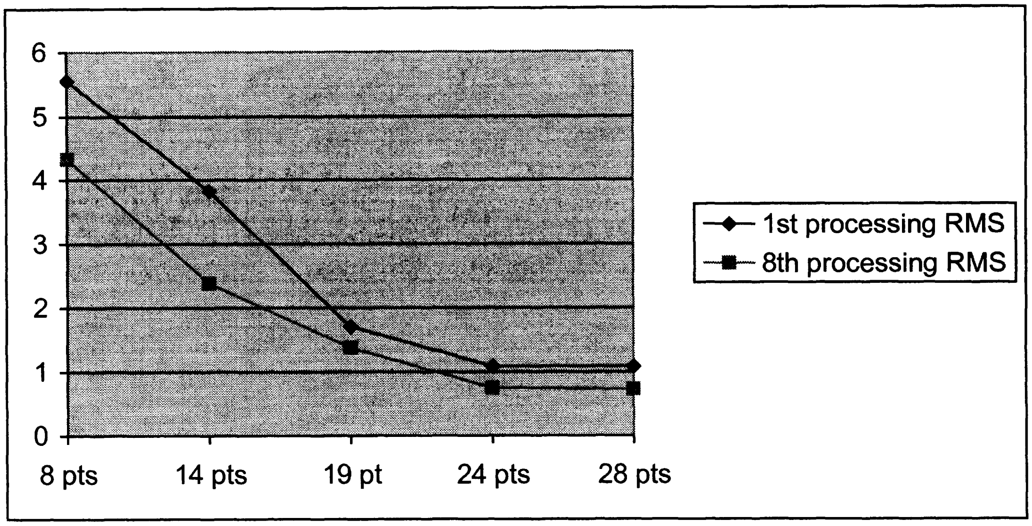


Figure 5.2 3-D RMS (in mm) before and after repeated processing for 5 well distributed control configurations of the plate test object

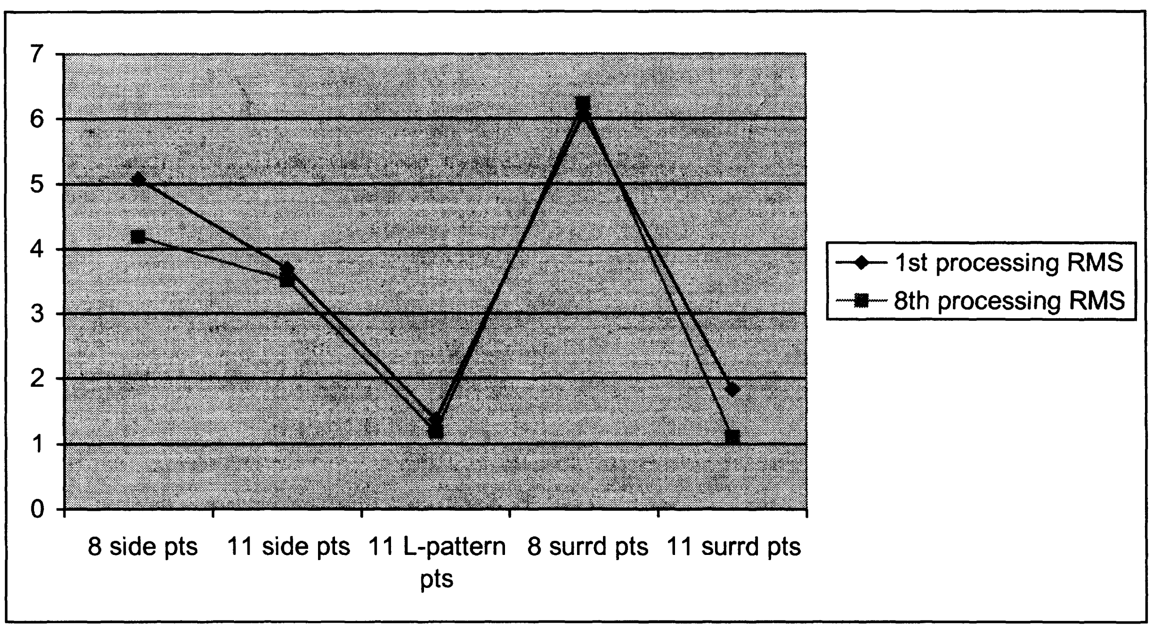


Figure 5.3 3-D RMS (in mm) before and after repeated processing for 5 control simulation cases of the plate test object

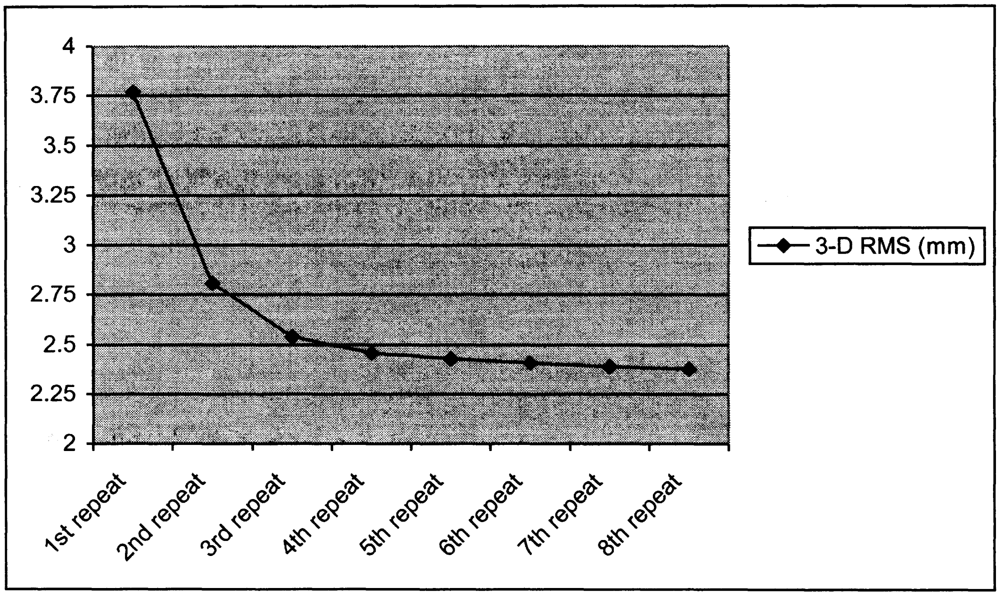


Figure 5.4 Improvement of 3-D RMS from each repeated processing for the well distributed control configuration with 14 control points and 47 check points

5.5.2 Repeated Processing for Digital Camera Images

5.5.2.1 Test Cases and Results

Repeated processing was tested for the digital camera images of both the small and the large test objects. It was found that generally much less significant improvement of the check point accuracy in object space could be achieved through the repeated processing compared with that achieved in the cases of the scanned hard copy images. The corresponding results presented in Section 3.2, 3.3 and Chapter 4 are therefore mostly not obtained from the repeated processing, only the results with improved accuracy of the check points were adopted.

Table 5.4 shows the RMS values obtained from the first processing and each of the four repeated processing in the well distributed control configuration case of the metal plate test object with 14 control points and 47 check points, the images used are the Kodak DC-50 digital camera images. It can be seen that the accuracy obtained from each processing is well kept at the same level of RMS values.

Table 5.5 shows the RMS values obtained from the first processing and each of the four repeated processing in the well distributed control configuration case of the wooden house test object with 27 control points and 22 check points, the images used are the Fujix DS-100 digital camera images. The accuracy obtained from different processing can be seen vibrating within a small range of accuracy. Slightly lower accuracy was achieved from the first and the third repeated processing.

Table 5.6 shows the exterior and interior orientation parameters and lens distortion coefficients from the first processing and the fourth repeated processing for the same case as in Table 5.4.

Table 5.4 Check point RMS from each repeated processing for the configuration with 14 well distributed control points and 47 check points on the metal plate test object (Kodak DC-50 images)

Repeat (modification) times	RMS (mm)				Max. discrepancy (mm)		
	X	Y	Z	3D	DX/pt	DY/pt	DZ/pt
1st processing	0.15	0.24	0.22	0.35	0.34/304	0.77/66	0.66/505
Md 1	0.14	0.24	0.20	0.34	0.30/63	0.84/66	0.56/505
Md 2	0.14	0.24	0.20	0.34	0.29/61	0.87/66	0.53/505
Md 3	0.14	0.24	0.20	0.34	0.32/61	0.88/66	0.52/505
Md 4	0.15	0.24	0.20	0.35	0.33/61	0.89/66	0.51/505

Table 5.5 Check point RMS from each repeated processing for the configuration with 27 well distributed control points and 22 check points on the wooden house test object (Fujix DS-100 images)

Repeat (modification) times	RMS (cm)				Max. discrepancy (cm)		
	X	Y	Z	3D	DX/pt	DY/pt	DZ/pt
1st processing	0.93	0.77	0.49	1.30	1.75/323	1.33/122	1.14/432
Md 1	0.97	0.91	0.60	1.46	2.10/432	1.81/432	1.40/432
Md 2	0.93	0.76	0.48	1.30	1.70/323	1.29/122	1.15/432
Md 3	1.02	0.93	0.62	1.51	2.05/432	1.70/432	1.41/432
Md 4	0.93	0.76	0.48	1.29	1.66/323	1.28/122	1.15/432

Table 5. 6 Interior and exterior orientation parameters and lens distortion coefficients from the first and the fourth processing for the same case as in Table 5.4

Processing times		The first processing			The fourth repeated processing		
Photo number		Photo 1	Photo 2	Photo 3	Photo 1	Photo 2	Photo 3
Camera station coordinates (cm) and rotation angles (degrees)	X	-6.42	-7.02	-1.23	-6.02	-7.17	-1.25
	Y	-57.20	-60.78	-11.83	-52.32	-61.30	-11.66
	Z	42.85	-1.03	64.52	39.43	-0.95	63.79
	ω	53.37	89.89	11.49	53.26	89.81	11.49
	φ	-6.96	-7.08	-1.97	-7.22	-7.15	-1.95
	κ	-1.93	0.60	-3.05	-1.92	0.63	-3.08
Interior orientation parameters (mm)	f	15.92	15.69	16.38	14.61	15.82	16.21
	x	2.79	2.78	2.78	2.78	2.78	2.77
	y	2.09	2.10	2.10	2.08	2.10	2.10
Lens distortion coefficients	K_1	1.87E-5	1.09E-5	6.13E-6	2.54E-5	2.79E-5	1.02E-5
	K_2	1.69E-4	8.39E-5	5.62E-5	2.59E-4	1.87E-4	1.18E-4
	P_1	-2.85E-7	-1.32E-7	1.32E-7	-1.18E-6	-3.93E-7	-2.12E-7
	P_2	4.10E-7	6.56E-8	-9.60E-8	1.22E-6	-1.41E-7	1.11E-7

5.5.2.2 Analysis of Results

1. The repeated processing with the software PM Pro for the digital camera images under test did not show accuracy improvement for the check points in object space in all the test cases. The repeated processing is therefore not recommended for digital camera images. Compared with the significant accuracy improvement achieved from the repeated processing for the scanned hard copy images, the reasons for the clearly different needs of the repeated processing between the digital camera images and scanned hard copy images are still to be investigated. Figure 5.5 illustrates a comparison between the changes of the check point 3-D RMS values from each of the four repeated processing for the well distributed control configuration with 14 control points plus 47 check points on the metal plate with the scanned hard copy images and the corresponding changes with the DC-50 digital camera images for the same control and check point configuration and processing times. Figure 5.6 illustrates the 3-D RMS values of the check points obtained from each of the four repeated processing for the Fujix DS-100 digital camera images of the wooden house with 27 well distributed control points and 22 check points.
2. Uncertainties of the camera parameters, especially the principal distance and the lens distortion coefficients for the same photograph solved by PM Pro from different repeated processing for the same case, were again experienced, as shown in Table 5.6.

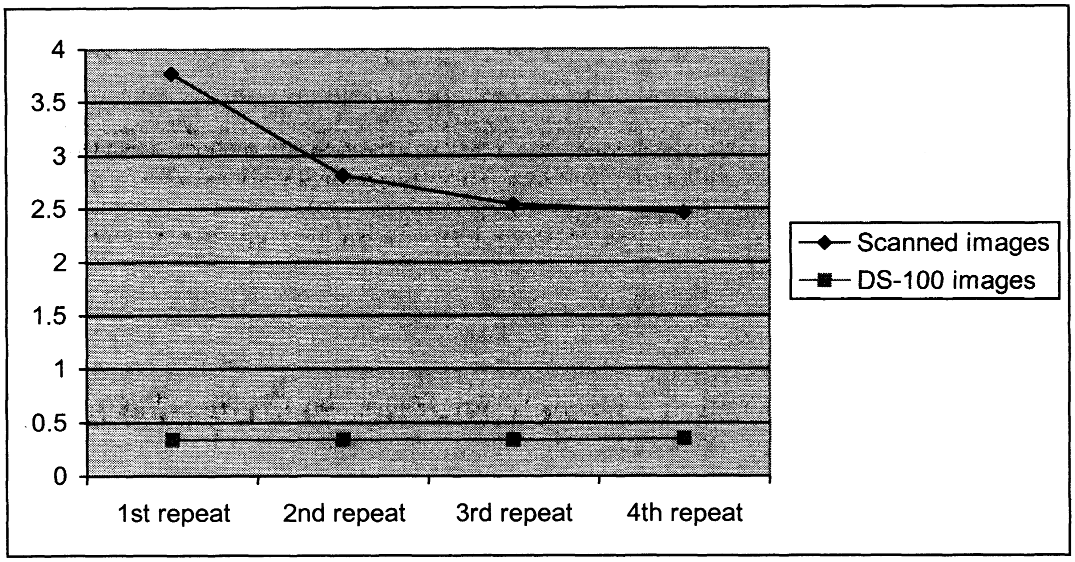


Figure 5.5 Check point 3-D RMS (mm) from 4 repeated processing for hard copy images and for DC-50 digital camera images for the same well distributed control configuration (14 control points + 47 check points) of the metal plate

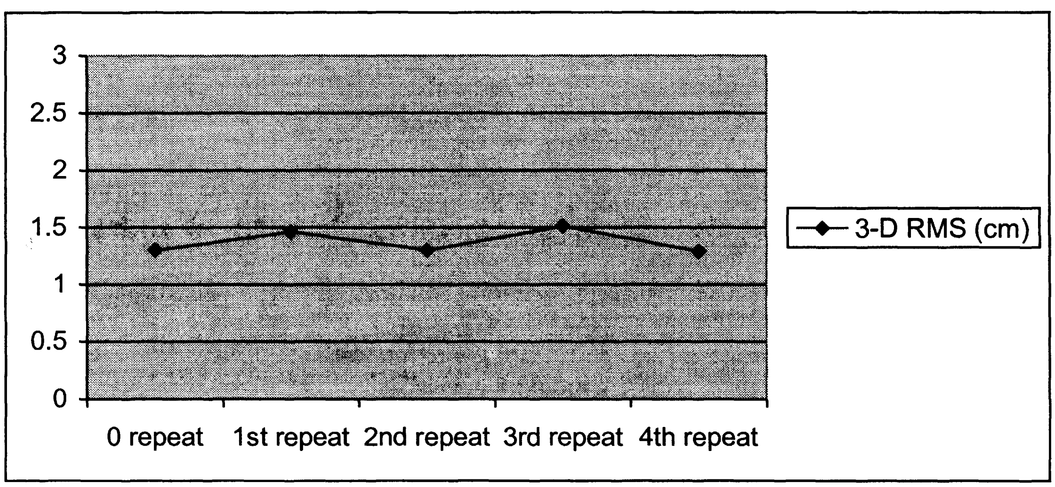


Figure 5.6 Check point 3-D RMS from 4 repeated processing for DS-100 images of the wooden house with 27 well distributed control points and 22 check points

5.6 Pseudo Camera Theory and Applications

5.6.1 Concept of Pseudo Camera

In analytical photogrammetric processing, it is a common practice that photo coordinates of the image points needed must be acquired as the basic data for various adjustments or calculations involving related photogrammetric formulas, such as collinearity equation, coplanarity equation, space resection and intersection, space similarity transformation and various polynomial transformations. These photo coordinates however, are often not measured or digitized from the original photographs taken by the original cameras, as is the cases of conventional aerial-photogrammetry. In close range photogrammetry and digital photogrammetry, the photo coordinates are often measured or digitized on enlarged, scanned and/or enhanced images.

Let the images on which the photo coordinates are finally measured or digitized be defined as the "final images", to be compared with the "original images" which are the images on the original photographs taken by the original cameras. In the theory of geometrical transformation, a frame of the final images is the result of one or more 2-D to 2-D perspective transformations from the corresponding frame of original images. A frame of the original images is the result of a 3-D to 2-D perspective transformation from the photographic object to the original photograph. Equation (4-1) expresses the transformations from a 3-D photographic object through original photograph to the final images (Faig et al. 1988).

$$\begin{bmatrix} x \\ y \\ 1 \end{bmatrix} = \begin{bmatrix} a_1 & b_1 & c_1 \\ a_2 & b_2 & c_2 \\ a_3 & b_3 & 1 \end{bmatrix} \begin{bmatrix} b_{11} & b_{12} & b_{13} & b_{14} \\ b_{21} & b_{22} & b_{23} & b_{24} \\ b_{31} & b_{32} & b_{33} & 1 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix} \tag{4-1}$$

Where x and y are the photo coordinates on the final image, X, Y and Z are the object space coordinates of the identical point in object space.

The first 3 by 3 matrix with 8 coefficients is the 2-D to 2-D perspective transformation coefficient matrix of photo enlargement or image scanning; the second 3 by 4 matrix with 11 coefficients is the 3-D to 2–D perspective transformation matrix from the photographic object to the original photograph. Every time when one more enlargement or scanning is applied, a 3 by 3 matrix should be multiplied to the left of the first matrix in equation (4-1), the whole resulting coefficient matrix however, is apparently always a 3 by 4 matrix no matter how many 2-D perspective transformations are superimposed onto equation (4-1). In other words, after a series of 2-D to 2-D transformations such as photo enlargement and image scanning from the original photograph, the resulting final images are equivalent to a frame of original images with a new set of transformation coefficients form the object to the final images. If we define the photograph containing the final images as the final photograph, this final photograph is applicable to any photogrammetric processing because of the equivalence to the original photograph. However, the interior and exterior orientation parameters of the final photograph are obviously not the same as the corresponding parameters on the original photograph. The final photograph with its interior and exterior orientation parameters and systematic image distortions is corresponding to a camera with these parameters and distortions in theory, this camera is defined as the pseudo camera.

A pseudo camera has all of the geometrical properties required by photogrammetry, although it does not necessarily exist physically in real life (Deng, 1988). It needs to be realized that the interior and exterior orientation parameters and systematic image distortion coefficients solved with the photo coordinates of a final photograph do not belong to the original camera, but to a pseudo camera. Only when the final images happen to be the original images, i.e. no additional 2-D to 2-D perspective transformations superimposed onto equation (4-1), it can become true that these camera parameters and image distortions solved belong to the original camera. This concept is however not always made clear in the literature, including the User Manual and the related text for the investigated software PM Pro, in which the interior and exterior orientation parameters solved with the final images are assigned to the original cameras for the purposes such as inverse camera. The term inverse camera employed in the software PM Pro means solving for the needed interior and exterior orientation parameters of an unknown camera based on control points.

The mismatching of the pseudo camera parameters with the original camera will not cause any problem in the cases where the basic purpose of the project is to solve for the object space coordinates on the photographic object, which are the most common cases in practical applications. The camera parameters are of little concern to the user under this circumstance. But when a reversal processing is required to determine the orientation parameters of the original camera from the final images formed by a series of superimposed perspective transformations from the original images, extra mathematical efforts are needed to develop the correct solution.

5.6.2 Applications of Pseudo Camera Theory

Pseudo camera theory was applied mainly in two aspects in this project. First, this concept explained why the camera parameters solved with the scanned images were so different from the expected parameters of the original cameras. The answer is simply that these camera parameters were corresponding to the pseudo cameras, instead of the original cameras. The scanned images used for the adjustments were not original images, they were final images transformed from the original images by perspective transformations. Table 5.7 shows the orientation parameters obtained from the adjustment for 3 cameras corresponding to the 3 photos (considering photo variant approach) of the scanned images of the metal plate with 28 well distributed control points and 33 check points. The initial values of these parameters as the program default are also listed. The nominal focal length is 50 mm on the original film based camera Olympus OM 10, this value is the same as the program default initial value of the principal distance.

Table 5.7 Adjustment result of orientation parameters for scanned images of the plate with 28 well distributed control points and 33 check points

Parameters		Result of adjustment			Program default initial values		
		Photo 1	Photo 2	Photo 3	Photo 1	Photo 2	Photo 3
Interior orientation parameters (mm)	f	64.091	65.892	64.815	50.000	Same as photo 1	Same as photo 1
	x	17.080	17.335	17.130	18.000		
	y	11.255	11.653	10.861	11.000		
Camera station coordinates (cm)	X	-5.408	-4.066	-5.886	100.000		
	Y	-45.280	-24.943	-52.835	100.000		
	Z	26.649	47.980	-6.249	100.000		
Camera rotation angles (degrees)	ω	59.188	28.483	94.938	-45.000		
	φ	-10.547	-9.475	-11.403	35.264		
	κ	-2.275	-4.063	0.186	150.000		

The large differences between the adjustment resulting values of *f* in Table 5.7 (64-66 mm) and the nominal focal length of the original camera (50 mm) were caused by two reasons. First, the values of *f* obtained from the adjustment are solutions for the principal distances, which inherently have significant differences from the focal length when the object distances are short, which is the case of this test (object distance was about 60 cm). Secondly, the resulting adjustment values of *f* are solutions of the principal distances of the pseudo cameras, not principal distances of the original cameras.

The second aspect of applying the concept of pseudo camera in this project was in the test of assigning arbitrary cameras with approximate parameters to pre-existing photographs for photogrammetric adjustment, assuming that the original camera and the corresponding parameters were unknown. The software PM Pro requires camera type and initial values of camera parameters as input information before adjustment. This requirement could not be neglected in any case, even when there were as many as 27 well distributed control points used in the adjustment. A test was made by assigning the camera type of "video camera" with the corresponding initial parameters to the 5 photographs taken with the digital camera Fujix DS-100 before adjustment. By comparing the result from this adjustment with that from the original adjustment where the camera type of "digital camera" with the corresponding initial parameters were assigned to the same photos of the same case, the same object space accuracy for the check points were obtained, but the solutions of the camera parameters from the two adjustments were different. The particular case for this comparison test was the well distributed control configuration with 27 control points and 22 check points on the wooden house. Table 5.8 shows the comparison of the check point RMS values. Table

5.9 shows the interior and exterior orientation parameters obtained from the two adjustments, the camera types and initial parameters provided by the program defaults are also listed.

Table 5.8 Check point RMS from two adjustments with digital and video cameras as initial camera types for DS-100 images of the house with 27 well distributed control points and 22 check points

Initial camera	RMS (cm)				Max. discrepancies (cm)		
	X	Y	Z	3D	DX/pt	DY/pt	DZ/pt
Digital	0.93	0.76	0.48	1.29	1.66/323	1.28/322	1.15/432
Video	0.82	0.96	0.51	1.37	1.84/311	2.15/311	1.53/311

Table 5.9 Orientation parameters from two adjustments with digital and video cameras as initial camera types for DS-100 images of the house with 27 well distributed control points and 22 check points

Initial cameras	Parameters		Result of adjustments					Initial values of program default	
	Photos		Photo 1	Photo 2	Photo 3	Photo 4	Photo 5	Photo 1	Photo 2, 3, 4, 5
Digital camera	Interior orientation (mm)	f	7.199	7.247	7.717	7.428	7.320	8.500	Same as Photo 1
		x	2.782	2.696	2.760	2.895	2.966	2.800	
		y	2.077	2.140	2.170	2.103	2.075	2.100	
	Camera station (cm)	X	-8978.79	-9300.98	-9335.97	-9720.43	-10305.67	100.000	
		Y	5490.74	4739.16	4298.12	4303.29	4435.65	100.000	
		Z	948.34	891.66	853.44	854.65	898.43	100.000	
	Camera rotation (degrees)	ω	-136.03	112.50	105.00	105.91	106.88	-45.000	
		φ	80.18	56.52	42.88	30.94	-1.83	35.264	
		κ	-133.36	-19.88	-10.88	-8.69	-2.07	150.000	
Video camera	Interior orientation (mm)	f	5.818	5.869	6.251	6.012	5.917	7.500	Same as Photo 1
		x	2.267	2.184	2.237	2.352	2.390	2.300	
		y	1.692	1.729	1.748	1.705	1.682	1.700	
	Camera station (cm)	X	-8980.94	-9300.18	-9335.41	-9720.94	-10305.96	100.000	
		Y	5490.18	4738.87	4297.03	4302.74	4437.04	100.000	
		Z	948.14	891.46	854.76	855.58	898.43	100.000	
	Camera rotation (degrees)	ω	-136.44	112.55	105.01	105.81	106.92	-45.000	
		φ	80.34	56.50	42.84	30.83	-1.75	35.264	
		κ	-132.96	-19.91	-10.88	-8.62	-2.08	150.000	

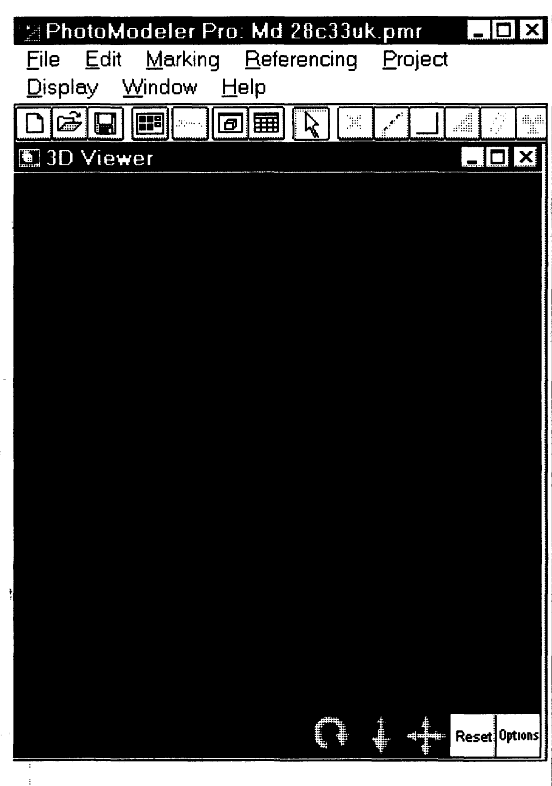
It was felt that the solutions for the orientation parameters obtained from the adjustments needed to be further confirmed, because of the uncertainties in solving for the orientation parameters with the software, as mentioned previously. In fact, the exterior orientation parameters for the two cases in Table 5.9 were found to be very close, and it was expected that the interior orientation parameters should also be very close. However, they are quite different, as shown in Table 5.9, even though all of the photos and points in the two cases were kept the same.

In spite of the apparent differences between the camera parameters for the same photographs solved with different control configurations, the 3-D views of the object position and camera stations provided in the software based on the results of the adjustments, were always found to be reasonable, for the relative positions of the object and the cameras. These cameras with the corresponding solutions for the orientation parameters should also be explained as certain type of pseudo cameras.

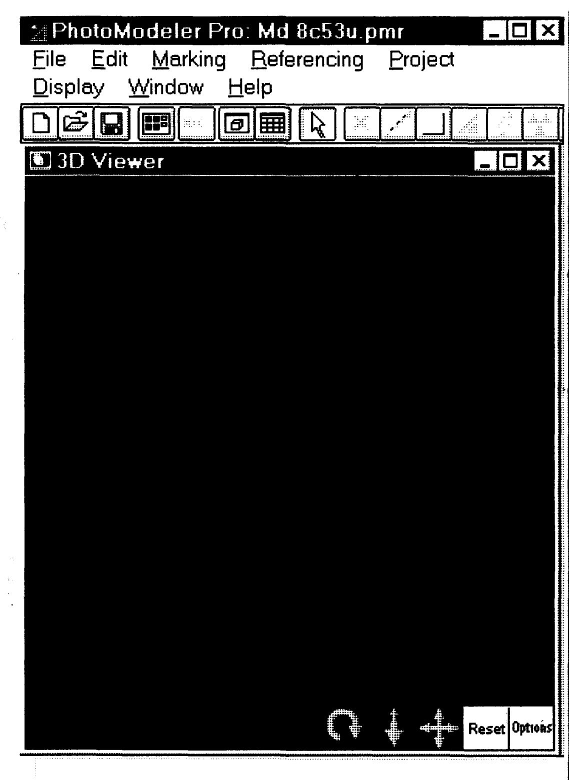
Table 5.10 shows the orientation parameters of 3 scanned photographs of the metal plate obtained with 2 different control configurations, namely the well distributed control configuration with 28 control points and 33 check points as the first case, and 8 control points and 53 check points as the second case. Figure 5.7 shows the 3-D views provided by the 3-D Viewer of PM Pro illustrating the 3-D positions of the object (plate) and the camera stations in these two cases. Both 3-D views in Figure 5.7 look reasonable while their camera station coordinates and rotation angles are in fact significantly different as shown in Table 5.10.

Table 5.10 Camera parameters of 3 scanned photos of the metal plate from 2 well distributed control configurations

Cases		28 control pts & 33 check pts			8 control pts & 53 check pts		
Photo number		Photo 1	Photo 2	Photo 3	Photo 1	Photo 2	Photo 3
Camera station coordinates (cm) And rotation angles (degrees)	X	-5.41	-4.07	-5.89	-5.50	-3.57	-5.83
	Y	-45.28	-24.94	-52.83	-57.25	-26.69	-56.64
	Z	26.65	47.98	-6.25	26.46	61.95	-16.27
	ω	59.19	28.48	94.94	64.79	24.52	104.55
	φ	-10.55	-9.48	-11.04	-9.72	-7.42	-8.26
	κ	-2.28	-4.06	0.19	-2.06	-4.00	0.51
Interior orientation parameters (mm)	f	64.09	65.89	64.81	77.34	83.79	85.97
	x	17.08	17.34	17.13	18.39	18.04	18.08
	y	11.26	11.65	10.86	11.34	11.03	10.95



a.



b.

Figure 5.7 3-D views of object and camera station positions from two well distributed control configurations on scanned images of the metal plate (a: 28 control points and 33 check points, b: 8 control points and 53 check points)

5.7 Output

The results of PM Pro can be exported from the Export menus in three different forms, namely in text form, 3-D data form and ortho-photo image form. The text form export includes the project text file and camera station file. The project text file is a specific ASCII file format of this software, containing the project description, input image information, control file data information and a number of parameters related to the process of the iterations in the adjustment. However, this output file is not user-friendly for general users, because no explanations could be found for the meaning of the codes in this file. It was felt that this file served mainly as a reference output file for the program designer to check the adjustment process. To get the adjustment result of the object space coordinates in text form, the proper way should be to save the data in the Table Viewer obtained after a successful adjustment.

The camera station text file contains the project description, object coordinates of the camera stations and targets, camera twisting angles, focal lengths and photo format sizes. The uncertainties of the camera parameters obtained from the adjustment remain as a problem when using the camera parameters. Camera parameters can also be saved and loaded as a specific camera file type (". cam" files) with this software.

The 3-D data forms in version 3.0j of PM Pro include Autodesk DXF (2D and 3D), Microsoft DirectX, Autodesk 3D Studio, Wavefront OBJ, VRML (1&2), and RAW. It is a competitive advantage of this software to provide 3-D output data for subsequent processes such as CAD or animation. Photo texture can be assigned to the 3-D surface elements in order to make the exporting 3-D model more lifelike while keeping good metric property at the same time. Cylinders determined in PM Pro can be exported in 3-D data formats in the form of centerlines, full cylinders (solids) or tessellated faces.

An ortho-photo of selected surface elements marked in a plane on the photographs successfully processed by PM Pro can be exported under the Ortho-photo Export menu. The scale of the ortho-photo however, needs to be determined by the user after exporting. Figure 5.8 is an ortho-photo export of the plane area surrounded by the four points of 311, 314, 344 and 341 on Wall 3 of the house (see Figure 1.3 and Figure 1.4 for the point and wall positions). This ortho-photo was extracted from the PM Pro processed DS-100 images with the well distributed control configuration of 28 control points and 22 check points.

Figure 5.8 Ortho photo output of Wall 3 on the wooden house from DS-100 images with 28 well distributed control points and 22 check points

As a more advanced method of outputting data which usually involves programming, data extractions from PM Pro can also be performed by using the DDE (Dynamic Data Exchange) interface provided by PM Pro. DDE clients written in proper Windows programming languages can be used with PM Pro (as a DDE server) for loading and saving of PMR files, marking of points and fiducials, obtaining 3-D point locations and cylinder information.

Chapter 6 Conclusions and Suggestions

In order to evaluate the software package PM Pro, extensive practical tests were conducted with three sets of different non-metric images for two test fields with different typical sizes. The images include scanned hard copy images and digital camera images taken with two different low-resolution digital cameras. Two test fields with accurate full 3-D control points were used, namely a 3-D metal plate test object with the dimensions of 17 by 17 by 4 centimetres, and the four joining walls of a wooden house with the approximate dimensions of 7 by 8 by 4 metres. The testing and evaluating was mainly aimed on investigating the photogrammetric performance of the software in terms of accuracy, reliability and flexibility. The appropriate strategies for utilizing this software for measuring different objects, similar to the test fields, with non-metric images were tested. The attainable accuracies were presented and practical recommendations for the optimal choices of the measuring methods are given. Comparisons between different control point configurations, different control frames pattern simulations, different images and different adjustment options were carried out and summarized. The major operational concerns for obtaining optimum results from the software for practical applications are presented. Some theoretical problems related to the proper use and possible improvement of this software or other similar software were discussed. These include the camera calibration schemes for non-metric images, influences of two different types of lens distortions, and the concept of pseudo cameras. Some problems that require further research are reported. The main conclusions drawn from this project are as follows:

1. The software package PhotoModeler Pro is a flexible tool of close range photogrammetric measurements for practical applications. The deliberate design of this software package has enabled it to be successfully used in non-photogrammetric environments where specific photogrammetric expertise and equipment are not necessarily available. However, the knowledge of photogrammetry will be helpful to make more efficient use of the software, in terms of the optimal project design ranging from control configuration, photography, point marking, and adjustment to result presentation, and in analyzing and solving of problems, if any, encountered in the applications of the software.
2. The multiple input/output formats and DDE interface provided by PM Pro made the software accessible to many of the currently popular software systems in 3-D modeling, animation, graphics and digital image processing. The compatibility with the other popular software systems, the applicability to non-photogrammetric environments, and the user-friendly tutorials and help tools make the software package competitive in the current market. The ratio of features vs. cost of PM Pro is attractive to users in a vast range of application fields, such as measurements and modeling in industrial and manufacturing environments, architecture, accident reconstruction and animation production. A particularly promising application field, worth of further investigation is the merging of close range photogrammetry with GIS (Geographic Information System) by employing PM Pro's readily provided features such as direct measurement on digital photographs.

3. The best accuracies obtained in this project for the two test fields and three different types of images are shown in Table 6.1. The range of the obtainable accuracies is acceptable to many of the practical applications.

Table 6.1 Best accuracy obtained for the 2 test fields and 3 different types of images with PM Pro

Test fields and images		Check point errors in object space (mm)		Distance errors in object space	
		Max. RMS of 3-D coordinate	Max. coordinate discrepancies	Average discrepancies (mm)	Average relative errors
Small test field	Scanned images	0.43	1.08	0.59	1/781
	Digital camera images	0.17	0.41	0.20	1/1635
Large test field and digital camera images		9.3	16.6	6.4	1/1684

The average errors of the distances do not necessarily represent the accuracies. If the relative distance accuracies were expressed by the ratios of the average discrepancies of the distances checked in the corresponding tests to the largest dimensions of the objects, the 3 relative errors in the most right column of Table 6.1 would become 1/412, 1/1216 and 1/1775. It is in fact still a question under discussion about what is the most appropriate indicator for the relative distance accuracy.

4. The minimum number of control points required by PM Pro for processing non-metric images taken with non-calibrated cameras are: no less than eight 3-D control points in one adjustment project with no less than seven 3-D control points on each photo.

5. The optimum numbers of well distributed control points for processing non-metric images with PM Pro are: 20 to 25 points for scanned hard copy images and 9 to 12 for digital camera images. The reason for the difference between the two types of images lies in the insensitivity of the accuracies from digital camera images to the changes in the number of control points used in the adjustments. High accuracies could be obtained for the digital camera images even with the minimum number of well-distributed control points.
6. Significantly higher accuracies were obtained from the digital camera images than from the scanned hard copy images under the same conditions. This is an encouraging feature for employing the fast developing digital cameras in photogrammetry. The reasons for this difference, primarily the modeling of the systematic image errors caused by scanning, still need to be investigated.
7. If well-distributed control points are not available, the optimum patterns for control frames for photogrammetric measurements of small objects are: firstly a surrounding pattern, secondly a half-surrounding pattern (L-pattern). A side pattern is generally not recommended because of the poor accuracy at the side direction. The small area control configuration for photogrammetric measurements of large objects such as for architectural structures is not recommended, because of the poor accuracy caused by the weak control geometry.
8. The photo-variant approach, where each photo is assigned an individual set of interior orientation parameters and of systematic image error correction parameters for self-calibration or on-the–job calibration of the cameras should

be utilized for analytical processing of non-metric images. Although it was reported that slightly different principal distances exist for different points on one photo (Li, 1999), the photo-variant approach remains as an effective way to ensure sufficient accuracy for practical applications. Pre-calibration of non-metric cameras is of trivial value due to the instability of interior orientation parameters between exposures.

9. Camera types and initial values of the interior and exterior orientation parameters are required by PM Pro as input information, and the approximations for the initial values influence the accuracy of the adjustment results.
10. Uncertainties and even failures in solving for the orientation parameters and lens distortion coefficients of non-metric cameras with PM Pro were experienced in some tests. This remains a problem to be investigated and solved.
11. Repeated processing was found generally necessary for ensuring best accuracies in dealing with scanned hard copy images by PM Pro. The appropriate repetition times are 4 to 8 according to the specific tests.
12. Users should be aware that every coordinate system to be used in PM Pro must be a right-handed system. Special care should be taken concerning the control coordinates provided by conventional topographic surveying methods, which often provide coordinates in left-handed systems.
13. The concept of pseudo camera can be applied to deal with multiple perspective transformations of images and analytical camera calibrations with

any photogrammetric model. It should be made clear that according to this theory the exterior and interior orientation parameters including lens distortions solved from the final images are generally not corresponding to the original cameras, but to pseudo cameras which do not necessarily exist physically.

14. A noticeable advantage of PM Pro is its continuous feature improvement through version upgrading. More than 10 versions have been upgraded since the initial version was released. The author was pleased to find that in version 3.1 which was released and upgraded on 29 April 1999, just before the completion of this report, the improper program default as reported in Section 3.3 has been handled by assigning to each photo an individual camera in the "inverse camera project", yet it was only limited in the "inverse camera project". The conflicting precision values reported in Section 5.2.3 have also been solved in version 3.1.

15. With the features mentioned in conclusions 1 and 2, and with the reliable accuracies of the object space coordinates that are acceptable to many practical applications, PhotoModeler is representing the proper development for the current close range photogrammetric software. This software is an excellent tool for applications with non-metric images where very high accuracy is not required. The outlook for PM Pro is promising, with the expected continuous improvements to the few remaining defects, such as self-calibration without conflicts, and hopefully, scanning and radiometric calibration being taken into account.

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