The Enlarger-Digitizer Approach: Accuracy and Reliability*

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ABSTRACT: A potentially economical system designed for the wide-spreading photogrammetric applications in a non-photogrammetric environment has been investigated and developed. This system makes use of a microcomputer and an enlarger-digitizer for image coordinate measurements.

In this effort, we evaluated the reliability and accuracy of the enlarger-digitizer approach and compared it against comparator-digitized image coordinates. The evaluation examined the terms of the individual transformation as well as the performance within a bundle block adjustment.

INTRODUCTION

Although photogrammetric data reduction can be performed by taking an entire digitized image as one unit, current photogrammetric techniques mainly work with the image coordinates of features of interest. In analytical photogrammetry, points are the most commonly used feature. Therefore, before the metric properties of any image can be utilized, the image points of interest have to be extracted and their image coordinates have to be determined. Often, a photogrammetric comparator is used as the photo-coordinate digitizer in this approach. In some cases, a stereoplotter is used to simulate either stereo- or mono-comparators (Ghosh, 1988). However, a two-dimensional cartographic digitizer or other coordinate measuring tool could be applied as well, especially when working with enlarged photographs. By using this method, the low resolution of the measuring system could be largely compensated for by the photographic enlargement. This method becomes even more practical when a microcomputer is serving as a working station for digitization. Adams (1980), Murai *et al.* (1980), Welch and Jordan (1983), Shih and Faig (1986), and Kim (1987) have reported examples of such applications.

ADVANTAGES AND PROBLEMS

There are two factors which are important in the enlarged photo approach. First, a small format camera is cheaper, lighter, more easily available, and suitable for mapping of small projects. Second, photogrammetric techniques have been found to be useful in many other professions. However, it is not advisable to invest in a comparator or a stereo-plotter for a small work-load. A good alternative would be to enlarge the photograph and then to use a simple coordinate measuring device. Photographic enlargement, which introduces some small errors, can improve the ratio of measuring resolution to accuracy. Shih and Faig (1986) reported on preliminary studies concerning the accuracy of analytical processing with the enlarger-digitizer approach.

The current resolution of high precision cartographic digitizers is 25 μm (0.001 inch), while the absolute accuracy is approximately three times the resolution. Rollin (1986) has recommended 127 μm (0.005 inch) as the acceptance criterion for a digitizer. Compared with a precision comparator, this is quite inferior. In order to compensate for this relatively low resolution, the original negatives were enlarged, and then the enlarged prints were measured on a cartographic digitizer. The idea is to effectively increase the resolution by working with a larger photo scale. Although the extra procedure introduces extra errors, the gain is expected to be larger than the trade-off.

The main advantages of this enlarger-digitizer approach are lower cost, a comfortable working environment, and no need for stereo-perception.

- *Cost.* As compared with specialized photogrammetric instruments, a cartographic digitizer is far less expensive and has much wider applications. The capital investment for a single task can thus be significantly reduced.
- *Comfortable working environment.* Most photogrammetric measuring instruments utilize binocular optics for viewing. When using them, the eyes have to focus to infinity. However, everything else, such as notes on the table, is at a much closer distance. Constantly adjusting focus between infinity and close range introduces extra constraints for the eyes.
- *No need for stereo-perception.* Although stereo vision is natural for human beings, precise measurements with stereo-perception require extensive practice. Schwarz (1984) reported that three to nine months of training are required for an observer to reach a minimum proficiency. Most people do not have this training. Furthermore, for some physical reasons, such as acuity differences between the left and right eyes, stereo-perception can become rather difficult to achieve. Even with normal vision, the "weight" for the signals from the two sides is usually different; for example, right-handed people are usually also "right-eyed" (Hilborn, 1984). Schwarz (1984) reported that "some 20-25% of the photogrammetry trainees, having passed successfully tests for their natural stereoscopic vision, do not have the measuring capability to make a good photogrammetrist."

These advantages of applying a cartographic digitizer for photogrammetric projects, however, are coupled with a serious restriction, namely, the digitizer's inherent low resolution and accuracy. This limits the direct application to certain circumstances such as when paper prints are used or when such low accuracy is sufficient (Kim, 1987; Reutebuch, 1987). The enlarger-digitizer approach has more general applications; however, additional problems are introduced with the "superimposed" two-perspective transformations and the associated lens distortions and film deformations.

Concerning the superimposed perspective transformations, their effect can be expressed by the following equation:

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

where the first 3 by 3 transformation matrix represents the two-dimensional perspective transformation coefficient matrix of the enlargement, while the second 3 by 4 matrix models the three-dimensional to two-dimensional perspective transformation from

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object to image. Clearly, the dimensions of the resulting coefficient matrix are 3 by 4, which means that the two "superimposed" perspective transformations are equivalent to another three-dimensional to two-dimensional perspective transformation. The unknown interior orientations of both physical projections will not cause problems. The resulting focal length can be determined by a simple scaling process, because the normal case is the most common situation for enlargement. In addition, Shih and Faig (1987) provided a general solution for the single photo case in the closed form.

The joint effects of lens distortions and film deformations are more complicated in this application. However, based on analytical evaluation, the additional parameter approach is expected to be effective.

Due to the allowable original format of most commercial photographic enlargers, 35-mm and 60-mm format cameras are recommended for this approach. The original negatives are enlarged 4 to 10 times, with the enlargement ratio depending on the size of the image points, as well as on the resolution of the original film. Bolt and Atkinson (1984) and Wester-Ebbinghaus (1980) have shown that the image resolution causes the major problem for the use of a small format camera for model aircraft and helicopter photography. For the enlargement ratio, the best size for the next step, namely plotting, could also be considered.

The enlarger-digitizer approach can be applied in conjunction with graphic plotting with stereoplotters as well. The enlarged photos are measured on a cartographic digitizer, and analytical processing commences. For example, a bundle block adjustment with additional parameters or the DLT (Direct Linear Transformation) method may be used. Finally, the enlarged photos can be utilized for direct contouring and plotting with a photogrammetric plotter.

There are two types of instruments which could be used for enlarging a photograph: the rectifier and the enlarger. The rectifier may be used not only to change the format of the photo but also to compensate for tilts; the photo could then fit into the tilt range of an analog plotter. The enlarger is recommended primarily for its cheaper price and more common availability. A rectifier may only be found in a photogrammetric environment, while an enlarger can be found in almost any photographic shop.

REPEATABILITY OF A CARTOGRAPHIC DIGITIZER

Concerning the accuracy of the digitizer measurements, Masry (1984) stated that

> "The performance of the operator is highly dependent upon the skill, dedication, and stamina of the person. The limits imposed by human physiology are seldom approached. For example, the eye can resolve about 500 lines per inch under bright illumination at about 10 inches. If suitable controls are provided, the positioning accuracy will be a function primarily of visual acuity. For non-mechanical positioning, operator accuracy will typically be about 0.010 inch (0.25mm)."

Experimentally, Rollin (1986) reported on a test performed at the British Ordinance Survey with 34 digitizers, some of which have been in service since 1972. The results range from 0.075 mm to 0.142 mm in terms of RMS in x and y as compared with precise grid coordinates. As a result, he recommended that, "the RMS vector error must not exceed 0.127 mm."

Independently, Oimoen (1987) tested a $2000 tablet digitizer with a resolution of 0.001 inch (0.025mm) and an accuracy to the nearest 0.01 inch (0.25mm), as claimed by the manufacturer. Each point on every photograph was digitized five times separately with a rejection criterion for re-measuring of 0.003 inches (0.076mm). The values were compared with the readings from a precision comparator with at least count of one micrometre. The RMS errors in x and y, respectively, were 0.098 mm and 0.113 mm.

At the Department of Surveying Engineering at the University of New Brunswick (UNBSE), several tests have been carried out with different test objects. The standard deviations from the repeated measurements are listed in Table 1. The obvious differences between the first nine photos and the last four photos are caused mainly by differences in targetting, i.e., the definition of the photo points. The first group is using a metal plate test body as used in Moniwa (1977), which has well-defined crosses as targets. The second one uses a box-string project from a UNBSE laboratory assignment, where depth of field problems cause the deterioration of the image quality. However, in both cases, a repeatability of less than 0.1 mm was achieved.

This manual digitization station was also utilized for a video project, in which the printed hard-copies from an ink-jet plotter were measured (Faig and Shih, 1988). Without rejecting any measurements, the standard deviations of the averaging process are presented in Table 2. For the first object, a plane, all targets were well defined. For the second object, the same test plate for a close-range application of a non-metric camera was used. In the video image, the grid points were better defined than the bolt points, while both of them were less defined than points in the images of plane objects. For all prints, all image corners have good definition. Although the standard deviation of the

Table 1. The Repeatability of the Digitizer

Test object	Enlarge ratio	Photo no.	No. of obs.	σ_x μm	σ_y μm	σ_o μm	σ_o unit scale
1	4	16	180	48.2	73.7	62.7	15.7
	4	17	153	40.6	66.0	56.4	14.1
	4	20	183	48.2	68.6	59.7	14.9
1	7	16	183	43.1	71.1	84.3	12.0
	7	17	183	60.9	78.7	70.3	10.0
	7	18	134	55.8	83.8	71.5	10.2
	7	19	182	53.3	91.4	75.9	10.8
	7	20	183	55.8	83.8	72.5	10.4
1	10	16	182	48.2	78.7	66.5	6.6
	10	17	150	43.1	60.9	53.2	5.3
	10	18	135	50.8	66.0	60.3	6.0
	10	19	183	48.2	66.0	59.5	6.0
	10	20	182	48.2	66.0	59.0	5.9
2	8	13	211	66.0	99.0	85.9	10.7
	8	14	267	60.9	73.6	68.1	8.5
	8	15	274	78.7	99.0	91.3	11.4
	8	22	315	68.5	83.8	78.3	9.8

Table 2. The Repeatability of Points with Different Quality

Test object	Photo no.	Type	No. of obs.	σ_x μm	σ^y μm	σ^o μm
plane	-	corner	64	48.2	53.3	48.4
	1	cross	105	58.4	58.4	59.3
	2	cross	105	66.0	66.0	67.4
	3	cross	105	78.7	66.0	74.5
plate	1	corner	16	50.8	60.9	57.5
	2	corner	20	66.0	76.2	72.5
	3	corner	20	78.7	88.9	84.2
	4	corner	20	91.4	78.7	86.1
plate	1	grid	180	99.0	86.3	95.0
	2	grid	144	104.1	101.6	104.2
	3	grid	144	116.8	121.9	120.6
	4	grid	144	160.0	134.6	148.9
plate	1	bolt	75	109.2	104.1	108.5
	2	bolt	100	154.9	218.4	190.4
	3	bolt	75	190.5	165.1	179.3
	4	bolt	100	157.4	152.4	156.1

TABLE 3. STANDARD DEVIATION OF SINGLE PHOTO TRANSFORMATION (μM)

Photo	16					17				
Enlargement	Orig.	4a	4b	7	10	Orig.	4a	4b	7	10
Affine to Original	-	2.04	2.80	1.37	1.66	-	1.58	2.32	1.34	1.21
Perspective to Orig.	-	1.26	1.86	0.96	0.97	-	1.13	1.46	0.91	0.80
DLT to Object	13.06	25.26	24.71	10.63	9.16	12.94	14.76	15.49	11.66	7.72

TABLE 4. THE RESULTING ACCURACY FROM BUNDLE BLOCK ADJUSTMENT RMSE, UNIT:IMAGE (μM), OBJECT (MM)

	Without APs					With APs				
	Image		Object Check Points			Image		Object Check Points		
Data	x	y	X	Y	Z	x	y	X	Y	Z
Orig. 3 photos	7.0	7.0	0.13	0.16	0.36	4.0	4.0	0.08	0.10	0.36
Orig. 5 photos	7.0	8.0	0.15	0.14	0.20	4.0	4.0	0.07	0.07	0.12
4 × 3 photos a	8.0	10.0	0.15	0.20	0.81	7.0	7.0	0.10	0.18	0.63
4 × 3 photos b	7.6	8.9	0.13	0.22	0.76	7.0	7.6	0.10	0.21	0.76
7 × 3 photos	6.5	6.5	0.13	0.15	0.36	5.1	5.1	0.09	0.09	0.34
7 × 5 photos	7.6	7.6	0.12	0.13	0.23	5.8	6.9	0.06	0.08	0.14
10 × 3 photos	5.3	5.8	0.11	0.14	0.20	3.5	3.5	0.07	0.06	0.17
10 × 5 photos	6.1	6.1	0.13	0.13	0.17	3.8	4.3	0.07	0.06	0.14

Object: plate;
No. of control points: 18 horizontal and 20 vertical
No. of check points: 34 horizontal and 32 vertical;

averaging process can be reduced to 1/3 by implementing a robust estimation procedure, the results provide an appreciation of how the pointing can disperse with different types of targets.

ACCURACY FROM SINGLE PHOTO TRANSFORMATION

The enlarger-digitizer measurements were transformed to the measurements of the original negative by using a two-dimensional affine transformation, and the results were compared with those obtained by using a perspective transformation. The resulting standard deviations are listed in Table 3, which show the perspective transformation effect in the enlargement as compared to the measuring error and other error sources. The numbers were scaled to conform to the original negative. The enlarger-digitizer measurements were then transformed to object space by means of a three-dimensional to two-dimensional perspective transformation (DLT) (Abdel-Aziz and Karara, 1971) without additional parameters. In Tables 3 and 4 are the results from two sets of independent image digitizations which were conducted by different persons at different times on four times enlargement.

Gross errors were realized as an important issue. In order to have the results of transformations compared on a common base, those and only those observations which have been identified as gross errors in the bundle block adjustment were removed. All sets of prints, which have been analyzed, show a similar trend; thus, only two of them are listed. It seems that the perspective transformation of the imaging process composed the major part of the error "budget," while the enlargement introduces only a relatively small part.

ACCURACY FROM BUNDLE BLOCK ADJUSTMENT

Concerning the errors introduced in the enlargement, Shih and Faig (1986) have indicated that the combined effect can be taken into account by the parameters in the final block adjustment. It has been found that the physical model for additional parameters as used in UNBASC-2 (Moniwa, 1977) provides better results than a third-order spherical harmonics model (El-Hakim, 1979). The latter has shown virtually no improvement over a bundle adjustment without additional parameters when applied to enlarged photography.

In Table 4, the results from the bundle block adjustment using UNBASC-2 are given. Two blocks were processed, one consisting of three-overlapping photographs, the second of five. For the four-times enlargement, only three of five were used.

CONCLUDING REMARKS

The experiments have shown that the enlarger-digitizer approach is feasible. However, precise pointing has been found to be very subjective and depends not only on the characteristics of the targets, but also on the operator. Although this is true for any coordinate measuring device, it is felt to be a more significant contribution to the error budget in this approach.

Concerning the pointing, Rollin (1986) stated that care must be taken, although being over-cautious can produce biased readings. Other precautions which are suitable for all digitization projects are important for this approach, such as a warm-up period and a constant orientation of the cursor because of eccentricity errors.

The second perspective transformation, introduced by the enlargement, can be combined with the three-dimensional to two-dimensional imaging perspective transformation, and can be modeled together by one three-dimensional to two-dimensional perspective transformation. The effects from lens distortion and film deformation of the enlargement were not dominant. These can both be effectively compensated by additional parameters together with the distortions from the first imaging process. The physical model for additional parameters has been shown to be better.

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