ON THE AUTOMATED ASSESSMENT OF GEOMETRIC SCANNER ACCURACY

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ABSTRACT

A system is presented to investigate the geometric accuracy of scanners. Evaluation procedures and algorithms are described to analyze various types of scanners, from the low cost DTP scanner to the high performance film scanner. Evaluation can be based on a test target which allows both, manual visual analysis as well as automated algorithm evaluation. An assessment of quality has to differentiate between local and global geometric accuracy. Experimental evaluation results were obtained with scanners using different scanning principles. Further the requirements of a reliable geometric accuracy test target are discussed.

KURZFASSUNG

Ein System zur automatischen Evaluierung der geometrischen Auflösung von Scannern wird präsentiert. Die vorgeschlagenen Evaluierungsprozeduren und Algorithmen ermöglichen die Untersuchung verschiedener Scannertypen, vom DTP Scanner bis zum hochgenauen Filmscanner. Die Evaluierung, welche auf einem Testmuster basiert, kann sowohl manuell visuell als auch automatisch erfolgen. Bei jeder Untersuchung muß zwischen globaler und lokaler geometrischer Genauigkeit unterschieden werden. Experimentuelle Resultate zeigen die Anwendbarkeit der vorgeschlagenen Methode zur Untersuchung unterschiedlicher Scanner. Weiters werden Überlegungen zum Entwurf und zur Anwendung von Geometrietestmustern diskutiert.

1 INTRODUCTION

Among other possibilities digitization by scanner is the most important way to obtain digital data from an analog image. Geometric resolution, geometric accuracy, radiometric resolution, colour reproduction and speed are topics which have to be considered in an assessment of quality. The geometric accuracy of a scanner is defined by its ability to create a geometrically exact reproduction of an analog image. Consequently the geometric accuracy is a measure which shows how accurate the geometric proportions of the original analog image are maintained in its digitized copy.

This work describes procedures to analyze the geometric accuracy for variuos types of scanners, but in particular for high performance film scanners. The evaluation can be based on well defined high accuracy test targets and automated algorithms using image processing. Specific algorithms have been implemented in a software system called SCANEVAL in order to achieve an objective, operator independent, easy to use, time saving and comparable process of geometric accuracy evaluation. Results may be used for a thorough comparison between different scanners as well as for detection of long term stability; they may also serve as a basis for geometric scanner calibration.

2 BACKGROUND

The geometric accuracy can be assesed by use of geometric accuracy test targets [Baltsavias, 1994b] [Seywald, 1994] [Simonis,1991]. The targets contain highly symmetric measuring marks distributed over the whole measuring area, where the mark's positions and distances between them are well defined. Local geometric accuracy is which is measured by means of marks in a relatively small area (e.g. 2cm x 2cm), whereas global geometric accuracy is measured across the entire scanning area (e.g. 20cm x 27cm). For geometric accuracy evaluation well known measuring mark positional values (x(i), y(i)) of the underlying analog target need to be compared with the values (x(i)', y(i)') obtained from the digitized image. A linear conformal or affine transformation of points has to be performed to relate the two co-ordinate systems to one another. Residual differences in x- and y-directions can now be used to calculate the absolute, relative global and local values of accuracy. The absolute errror is expressed in pixels or mm. Relative accuracy is obtained by relating the error of the distance between two marks to the distance itself.

3 SCANNING PRINCIPLES

Image scanners can be classified according to their main technologies. With regard to geometric accuracy basically one has to distinguish between flatbed and drum scanners. The configuration of the built-in photo-detector is an additional criterion to characterize scanners. Image sensor technologies [Baltsavias, 1994c] are :

- point sensors,
- linear array sensors,
- square array sensors.

For geometrically high accurate scanning the fled-bed principle currently is the the preferred technology.

The number of tiles or swaths to be sewed together to one scan depends highly on the dimension of scanners the photodetector. Inside an individual scanning swath sources of error are lens distortion, lack of focus, CCD noise, rotation and translation of the sensor and lighting errors. Using linear array technology large images at contemporary high resolutions can be achieved by scanning the image with multiple swaths and stitching adjacent swaths together. Scanning with square array sensors [Leberl, 1992] may require the assemblage of neighboring tiles geometrically and radiometrically exact. In these scanning approaches geometric errors can be produced due to inaccurate assembly of neighboring swaths or tiles. Since it is usually easier to keep the mechanical positioning error of the sensor low for small scanning regions than for large areas. However different scanning technologies can deliver different types and different quantities of geometric errors.

4 TARGET DESIGN

Geometric scanner properties from DTP scanner to the high performance film scanner with geometric resolutions from 400 dpi to 5000 dpi have been investigated using both, glass and film based test targets. As a result of investigations a suitable high contrast film based geometric accuracy test target is proposed, which allows automated but also interactive geometric accuracy evaluation. The aim is to obtain both, global as well as local geometric accuracy out of one digitized target. This leads to the need of an adequate spacing between measuring marks. The higher the density of measuring marks in the target, the better is the ability to detect errors which can be missed otherwise. The dimension of the scanner's built-in CCD arrays leads itself to the limitation of the width of one scanning swath or tile. Currently linear CCD arrays from 300 pixels up to 8000 pixels and square array CCD's up to 2000 x 2000 pixels are used as scanner photo-detectors. Depending on the magnification of the optics different areas on the scanning plane are covered by the photo-detectors.

When using a target with a low measuring mark density, possible errors in between two marks cannot be detected and therefore they can be overlooked. An extended number of tests was carried out to determine the feasible number of measuring marks distributed over the test target to produce a sensible and precise geometric accuracy result for various types of scanners. Preferably the target would be available on a glass plate to avoid sensitivity to changes in temperature. However, many scanners are unable to cope with glass plates. Therefore a film based target will need to be available. For film targets it is proposed that a five degree change in temperature can cause a change in length of 12 μm [Wolber, 1991]. Normally a slight change of distances between marks due to temperature variations does not have an influence on measuring accuracy obtained after a Helmert or affine transformation, as long as a global change is affecting the whole target equally. Additionally a general useable target has to be designed to support transparent as well as opaque scanning.

The marks ought to be symmetric (circles, squares, cross-hair, see Figure 1) and their coordinates need to be measured on a precision instrument, e.g. an analytical photogrammetric plotter. Generally, the shape of the measuring mark depends on the type of evaluation process. The circular and square marks are better suited when evaluating by means of a center finding algorithm. Matchig of point positions by correlation is a technique where symmetric marks, especially filled circles or squares are to be preferred. The more common cross-hair is perhaps desired for manual assessments on a computer screen. Former investigations show that measuring marks to be centered by a centering algorithm must have a diameter of at least 4 pixels to achieve a centering accuracy which is sufficient [Trinder, 1989] [Maalen, 1993]. This has to be taken into account also when investigating low resolution scanners, where it leads to the need of relatively large measuring marks. It is of main importance for evaluation by an algorithm to ensure high contrast which allows that the measuring marks are distinct from a target's background and therefore can be segmented easily. As a result we have designed a target as shown in Figure 2, suitable for the entire range of low resolution DTP to high resolution film scanners, flat-bed and drum devices, opaque and transparent systems.

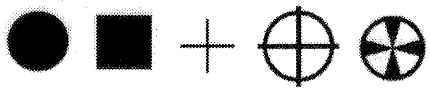

Figure 1: A collection of possible measuring marks digitized on a DTP scanner. From left to right: circular mark; quadratic mark; cross-hair; circled cross-hair; cross-hair with arrows.

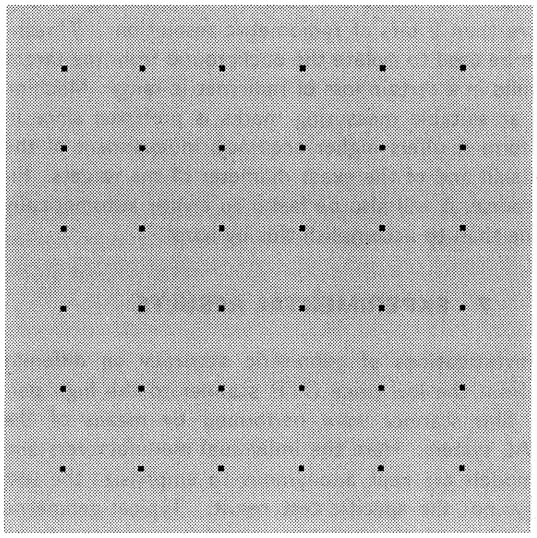

Figure 2: A subsection of the high contrast geometric accuracy target containing 1440 (48x30) measuring marks uniformly distributed over an area of 23cm x 16cm. The distance between neighboring marks is 0.5cm. The dimensions of the quadratic marks are 0.34mm x 0.34mm.

5 VISUAL ANALYSIS

The center of a digitized mark has to be found visually by placing a cross-hair cursor at the desired location of the mark. This requires the availability of a zooming function to find the mark with sub-pixel accuracy. It should be possible to determine the center manually with an RMS error of typically 5 % of a pixel [Trinder, 1987]. Manual cross-hair pointing precision can deteriorate as target sizes increase. Additional errors can occur due to asymmetric distribution of the pixels on the target and due to low signal to noise ratio (SNR). The geometric accuracy of the scanner is then obtained from computations comparing the measured positions of digitized marks with those known on the analog original. However, due to the significant effort for manually measuring a large number of marks (e.g. 600 marks) on a computer screen it is essential that visual analysis only should support the automated investigation. Support can be needed for verification of unusual, dubious or obviously false results obtained by automatic evaluation.

6 AUTOMATED ANALYSIS

When locating the center of measuring marks with sub-pixel accuracy a wide range of techniques is proposed and these can be grouped as centroiding, correlation, edge analysis and shape based techniques [Trinder, 1989] [West, 1990]. Automated measurement is possible with an accuracy of better than ± 0.1 pixels. With the scanner evaluation system the center of circular digital dots and other symmetric measuring marks can be found automatically with subpixel accuracy by means of a weighted center finding algorithm [Trinder, 1989]. According to the former investigations with a target diameter of 4 pixels of [Maalen, 1993] the automated algorithms deliver the best results. Target sizes of less than 4 pixels have to be avoided due to large deterioration of precision, whereas the precision is slightly lower but sufficient for more than 4 pixels of diameter. The dynamic range of the measuring marks will not significantly influence the accuracy of centering as long it has more than 2 bits of radiometric resolution . Thresholding can be used to isolate the background from the target which results in a certain loss of radiometric range. Machine centering at suitable measuring marks is preferred since in the long term it offers higher accuracy, independent of the operators skill and of the exact diameter of the targets. Finally, of course, it will also be faster to center automatically by machine than to accomplish this by hand.

7 EXPERIMENTAL RESULTS

Various investigations of geometric accuracy on different scanners from the low price DTP scanner to the high performance film scanner were performed by means of the SCANEVAL system. Here the individual manufactorers and scanner models are kept anonymous to emphasize the test technology, not the specific test result. Typical geometric errors according to the scanners scanning principle can be obtained by scanning and analyzing the geometric accuracy target.

7.1 Single line CCD Scanner

Figure 3 shows the error vectors for a DTP scanner using single line CCD technology. The change of vector orientation in the scanning direction indicates that the speed of the CCD linear array is not stable when moving over the scanning area. Consequently the resulting real pixel size is varying over the scanning region and is directly proportional to residual variations.

7.2 Multiple swath line CCD scanner

The residual error vectors obtained after an affine transformation for a widely distributed high performance flatbed scanner can be seen in Figure 4. In this case adjacent scanning swaths are stitched together to one large digital image. The changing vector orientations in scanning direction indicate mechanical misalignment of the line array CCD when scanning neighboring swaths.

7.3 Square array CCD scanner

The residual error vectors for a high performance film scanner working with the square array CCD principle are shown in Figure 5. To avoid geometric errors adjacent tiles have to be assembled geometrically and radiometrically.

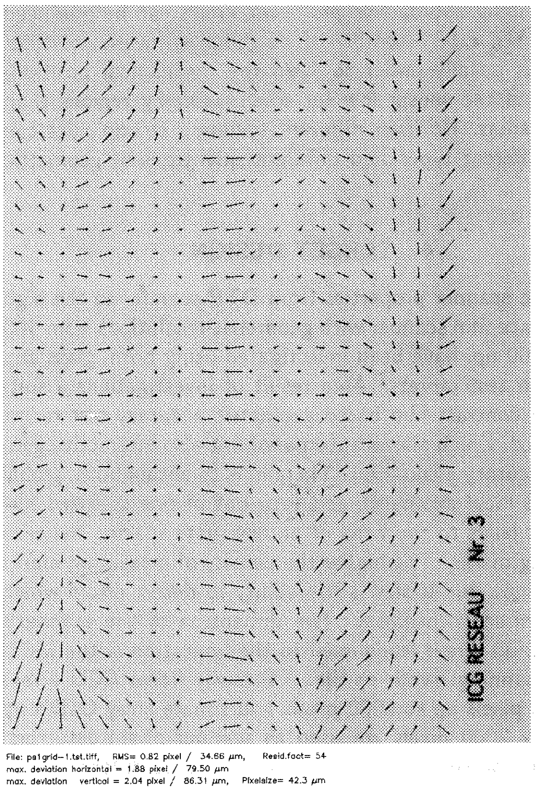

Figure 3: Residual error vectors when evaluating a test area of 11cm x 16 cm, including 19 x 30 measuring marks. Here the scanning resolution is 600dpi ($42 \mu m$). The r.m.s. deviation from ideal mark position obtained by affine transform is ± 35 μm. Maximum deviations are 74 μm horizontally and 87 μm vertically. error vector magnification: 54; swath scan direction: left to right;

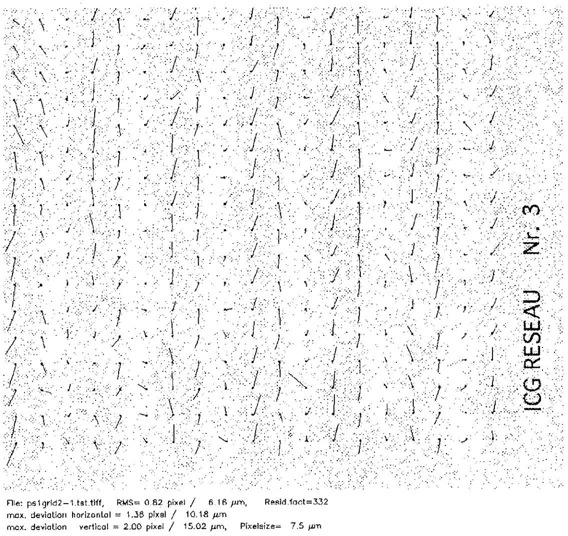

Figure 4: A subsection of resulting residual error vectors when evaluating a test area of 11cm x 16 cm, including 19 x 30 measuring marks. Orientation of error vectors changes in neighbored measuring mark columns. This leads to the assumption that adjacent scanning swaths are misaligned. Affine transform; Pixelsize=$7.5 \mu m$; RMS error=± $6.2 \mu m$; error vector magnification: 332; swath scan direction: top to bottom.

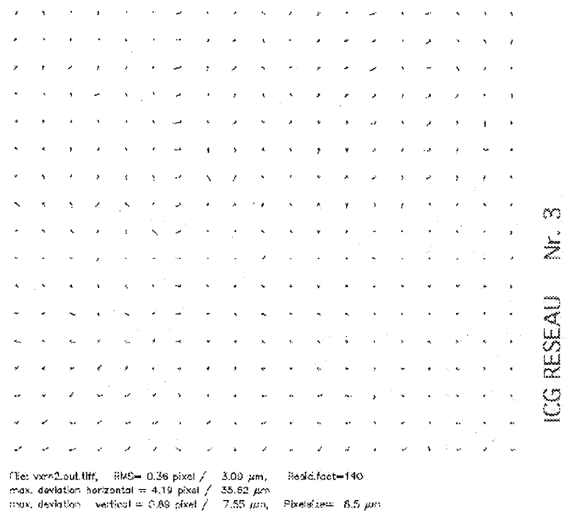

Figure 5: Geometric accuracy investigation of a square array CCD scanner. A subsection of the resulting residual error vectors shows the accuracy of the alignment of adjacent tiles. If tiles are put together inexactly it can be seen from direction and dimension of error vectors. Affine transform; Pixelsize=8.5μm; RMS error=± 3.1μm; error vector magnification: 140.

7.4 Number of measuring marks

Table 1 shows the dependence of error vectors from the number of measuring marks lying in the investigated area. It can be seen that at least a certain number of marks is necessary to make a meaningful evaluation of geometric scanner accuracy by use of linear conformal or 6 parameter affine traansformation. In this case of global geometric accuracy evaluation the investigated area covers more than one of the tiles made by the scanner for digitization.

numb. of marks	trans-form.	RMS error	max horiz.	max vert.
		pixel/μm	pixel/μm	pixel/μm
19x30	helm.	0.5/4.7	1.1/9.1	1.1/9.1
	aff.	0.4/4.1	1.1/9.1	0.9/7.4
10x15	helm.	0.5/4.4	0.7/5.9	1.4/12.1
	aff.	0.4/4.1	0.7/5.7	1.3/10.7
5x8	helm.	0.5/4.4	0.6/5.0	1.1/9.6
	aff.	0.4/4.1	0.5/4.3	1.2/10.4
3x4	helm.	0.4/4.1	0.6/5.2	0.9/7.5
	aff.	0.4/4.0	0.3/2.9	0.7/6.0
3x3	helm.	0.3/3.5	0.4/3.5	0.5/4.7
	aff.	0.3/2.3	0.3/2.3	0.4/3.6

Table 1: Residual error vectors according to different numbers of test marks distributed evenly. Affine and Helmert transformations are used for evaluation. The investigated area is about 9 cm x 15 cm at 3000 dpi geometric scanner resolution. It is evident that the RMS errror decreases as the redundancy in the number of measuring marks decreases.

Scanner	trans-form.	res.	RMS err.	max. hor.	max. vert.
		μm	μm	μm	μm
DTP	helm.	63.6	108.0	207.1	161.9
Scanner 1	aff.	63.6	16.4	30.5	45.2
DTP	helm.	42.3	96.9	156.1	235.4
Scanner 2	aff.	42.3	35.0	74.5	87.7
Drum	helm.	10.4	17.8	29.8	25.4
Scanner	aff.	10.4	6.3	15.3	11.8
Photogr.	helm.	7.5	7.3	9.8	19.42
Scanner 1	aff.	7.5	6.2	15.2	14.6
Photogr.	helm.	8.5	4.75	9.2	9.7
Scanner 2	aff.	8.5	3.2	9.0	7.43

Table 2: Residual error vectors in μm according to different scanners. Evaluated were two low cost DTP scanners and three high performance film scanners. The target measuring area utilized for the testscans is 11 cm x 16 cm except on the Drum Scanner where a reduced measuring region of 5cm x 5 cm is used. DTP Scanner 1, DTP Scanner 2 ... single line CCD principle; Photogrammeric Scanner 1 ... Multiple swath line; Photogr. Scanner 2 ... Square Array CCD.

Scanner	trans-form.	res.	RMS err.	max. hor.	max. vert.
		pixel	pixel	pixel	pixel
DTP	helm.	63.6	1.7	3.3	2.5
Scanner 1	aff.	63.6	0.3	0.7	0.5
DTP	helm.	42.3	2.3	3.7	5.6
Scanner 2	aff.	42.3	0.8	1.8	2.0
Drum	helm.	10.4	1.7	2.9	2.4
Scanner	aff.	10.4	0.6	1.5	1.1
Photogr.	helm.	7.5	1.0	1.3	2.6
Scanner 1	aff.	7.5	0.8	1.9	2.0
Photogr.	helm.	8.5	0.5	1.1	1.1
Scanner 2	aff.	8.5	0.4	1.1	0.9

Table 3: Residual error vectors in pixel according to different scanners. DTP Scanner 1, DTP Scanner 2 ... single line CCD principle; Photogr. Scanner 1 ... Multiple swath line; Photogr. Scanner 2 ... Square Array CCD.

7.5 Comparison of different scanners

Error vectors for conformal transformation and affine transformation obtained when evaluating the geometric accuracy performance of different scanners can be seen in Table 2 and 3. Additionally the tables show the maximum errors in horizontal and vertical scanning direction. The resulting error vectors show significant size variations for different types of scanners. The geometric accuracy of high accurate, high performance photogrammetric scanners surpasses the accuracy delivered by the evaluated DTP and prepress scanners. Although the investigated drum scanner was expected to be geometrically inaccurate due to its working principle, its residual errors after an affine transformation lie in the range of the high performance scanners which have been evaluated. However, the evaluated area was only 5cm x 5cm and a lack of flatness of the film target may thus not be effective. The error may increase in a larger scanning area. When comparing the RMS errrors for Helmert and affine transformations it is evident that the high performance scanners produce errors which lie in the same range, indicating the absence of affine distortions. The other scanners deliver great differences between affine error and Helmert errors. Consequently this factor may be an additional criterion in an assessment of a scanner's geometric quality. A large RMS error difference between Helmert transformation and affine transformation leads to the the conclusion that the evaluated scanner produces a difference in pixelsize between x and y directions. When scanning with the single line principle this may be caused by unstable or incorrect speed of the moving CCD.

7.6 Repeatability measurements

The repeatability of geometric accuracy results for a DTP scanner and a high performance film scanner is assessed in Table 4. For the repeatability measurements every subsequent test scan has to be executed at the same and highly stable conditions. Therefore it is essential to place the test target for every scan at exactly the same position on the scanning region when doing the repeatability test. Further possible vibrations of the scanner caused by the scanners environment, which can lead to additional unwanted digitizing errors, have to be avoided.

Scanner	trans- form.	res.	Mean of RMS error	Stdev of RMS error
		μm/dpi	μm/pixel	μm
DTP scanner	helm.	63.6/400	108.0/1.7	0.3
	aff.	63.6/400	17.0/0.3	0.3
high perf. scanner	helm.	8.5/3000	0.5/4.7	0.1
	aff.	8.5/3000	0.4/3.2	0.01

Table 4: An investigation of measuring repeatability for a DTP and a high performance scanner. Geometric accuracy evaluation is taken for 10 mutually independent scans, where the test target for every scan is placed exactly on the same position.

The repeatability of the investigated DTP scanner seems to be very good. The Mean of RMS errors and its standard deviation are computed for 10 mutually independent scans of the geomeric accuracy test target. The evaluation is based on a Helmert transformation as well as for affine transformation. It is evident that the geometric error produced by the DTP scanner has a large stable portion and is therefore highly reproduceable. The remaining random variation of the error is in this case very small. Consequently an increase of geometric accuracy properties of the DTP scanner could possibly be achieved by the use of a calibration grid and built in calibration procedures. However the maximum resolution is too low to use the scanner as a photogrammetric device. When investigating the data delivered by the high performance geometric accuracy scanner, the change of geometric RMS error vectors between subsequent images is infinitely small, which shows the high geometric performance of this type of scanner.

8 CONCLUSION

A system for the geometric accuracy evaluation of scanners is presented. It can be used to obtain the geometric properties of various types of scanners, from the low cost DTP to high performance film devices. The analysis is possible by manual visual or fully automated methods using algorithms and achieves an accuracy which is sufficient for detection of local as well as global geometric behavior. It can be shown that the precision of the scanner investigation is highly dependent on the appearance of the underlying geometric accuracy target. Visual analysis may result in a bias by a specific human analyst. Therefore, and for reasons of economy automated algorithms are prefered to produce test results. Of course visual analysis will continue as an important part of a scanner's evaluation because visual analysis is the only way to detect visual artifacts. Scanner evaluation results may by used for comparison between scanners as well as for detection of long term stability and can serve as a basis of geometric scanner calibration. The experimental results show the usability of the proposed algorithms implemented in the SCANEVAL system for geometric accuracy evaluation.

9 ACKNOWLEDGMENT

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