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NOVEL HIGH-PRECISION PHOTOGRAMMETRIC SCANNING

Michael Gruber[*)] , Franz W. Leberl[**)1] and Gerhard Thallinger[***)]

[*)]Institute for Computer Vision and Graphics, Technical University Graz
Münzgrabenstr. 11, A-8010 Graz, Austria; gruber@icg.tu-graz.ac.at
[**)]Vexcel Corp., 4909 Nautilus Ct., Boulder, Colorado, franz@vexcel.com
[***)]Vexcel Imaging GmbH Graz
Burggasse 4, A-8010 Graz, Austria; ggt@vexcel.co.at

ABSTRACT

Scanning for photogrammetric purposes requires that particular attention be paid to geometric accuracy and throughput, while radiometric accuracy, range and color have so far been of a somewhat lesser concern. This has led the photogrammetric industry to rely on specially designed and built photogrammetric scanners with optimized speed and geometric accuracy. Geometric accuracy is typically obtained in the same manner as in analytical plotters, i.e. by precise mechanical motion units. This approach combined with the production of only small numbers of units just for the photogrammetric market and has resulted in a significant cost for such devices.

It has often been argued that this situation differs from that in other application domains, for example in the graphic arts industry. Recommendations have therefore occasionally been made in the past to employ so-called graphic arts scanners for photogrammetry. These have not been accepted because the geometric accuracy of these products does not inspire confidence in their applicability to photogrammetric precision work. The idea of simply calibrating such scanners has not found much acceptance either, and the suspicion remains that such devices are inherently geometrically unstable. Yet, the radiometric performance of such graphic arts scanners has in the past often been found remarkable and well beyond that usually found in devices built for photogrammetric applications.

This paper reports about a new photogrammetric scanner whose underlying technology addresses both, high geometric accuracy and high radiometric quality. We will show by means of tests performed on this novel UltraScan5000 flat bed scanner that it satisfies not only high-level radiometric demands with density ranges of 3.4D and better, and with full color capabilities, but achieves also the high geometric accuracy of about ± 1 µm needed for the most demanding photogrammetric applications. We demonstrate with calibration grids and actual photography that the scanning accuracy satisfies the requirements to produce high-precision photogrammetric and GIS-mapping products such as point coordinates, ortho-photos, digital elevation models and planimetric GIS-data.

1. INTRODUCTION

Large format digital images are being produced by film scanners digitizing large format analog photography. This is particularly true in the field of softcopy photogrammetry, where aerial images with a typical size of 9" x 9" need to be processed and analyzed. Digitization of these analog images may produce pixel arrays of up to 30k by 30k pixels or even more if motion-compensated high resolution aerial film is being used. This contrasts with digital cameras based on area CCDs that currently operate with a maximum of perhaps 7k by 9k sensor elements, however at comparatively high cost and relatively low performance. This persistent state of affairs

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[1] Currently on leave from the Institute for Computer Graphics and Vision, Technical University Graz, Austria.

has ensured an ongoing and even growing role for film scanners as an essential part of digital photogrammetric systems.

Film scanners have been in use for over 10 years in photogrammetric applications, and perhaps as many as 400 may now been in use world wide (Baltsavias, 1998). The most important features of the products are their geometric accuracy, throughput, geometric resolution, radiometric accuracy and density range, and the capability of scanning the entire image format of typically 9” by 9” in one single step. Currently most products are based on a precise optical and mechanical implementation and are specialized for applications just in the photogrammetric market. These factors conspire to produce an offering at relatively high costs of such specialized scanners.

We present in this paper a new, innovative flat bed scanning system denoted as UltraScan5000[2]. The photogrammetric accuracy is being accomplished by means of a unique on-line calibration method that combines with a factory-calibration to ensure that the acceptable $\pm$1 µm geometric uncertainties are not being violated. We will illustrate results from this scanner in the form of measurements with test objects such as resolution targets, gray scales and geometric reference grids.

2. ABOUT FLAT BED SCANNING

2.1 The Advent of Flatbed Scanning

Flatbed scanners are widely used in desktop publishing and the so-called graphic arts. Compared with drum scanners such flatbed scanners offer a higher throughput during operation, more handling convenience and a lower price. As the quality of illumination, the density range, the color performance, format and geometric resolution increase, so does the cost of such systems. Based on the type of sensor, we distinguish between linear and square array scanners. For both types the sensor cannot cover the entire image area if scanning is to be done at high geometric resolutions. Therefore a mechanical unit is needed to move the sensor over the image plane. The accuracy of this motion assembly is significant for the definition of the geometric accuracy of the scanned image.

2.2 Square Array Sensing

Using square array sensors, the scanning process is subdivided into a sequence of static grabbing steps, wherein a small portion of the image is digitized at each step (cf. Fig. 1a). Thus the designation as “stare and step” method. These image tiles have to be transformed into the coordinate system of the output production image. The brute force approach is to use precise mechanical motion to ensure that adjacent “stares” fit seamlessly together. Leberl et al. (1992) presented an alternative method for tiling that does not rely on high mechanical accuracy. Instead , the mechanical accuracy of a square array scanner was enhanced by observing a reseau pattern. As an image tile is grabbed during the scanning operation it is transformed into the coordinate system of the reseau and geometrically rectified in the process. A small overlapping area among the individual image tiles serves to adjust the radiometric properties of the image patches to one to another and to ensure the seamless transition from one individual tile to another. The benefit of this method is not only a reduced need for mechanical accuracy of the scanner but also the establishment of a permanent and on-line self-calibration of the device[3] (Leberl et al., 1990a,b).

2.3 Linear Array Sensing

Linear CCD detector arrays promise a higher radiometric resolution, a wider density range and greater throughput, particularly with color images, than square array CCD sensors. However, their use requires a different approach to scanning. The stop-and-go or step-and-stare process of area CCDs has to be changed into a kinematic process, such that the linear CCD is continuously moving over the image (cf. Fig. 1b). Large images which may cover more than the area of a single path of the CCD array need to be digitized along multiple paths (cf. Fig. 1c). As this process occurs, each individual subscan must be made to fit with its adjacent subscans to produce a seamless output image.

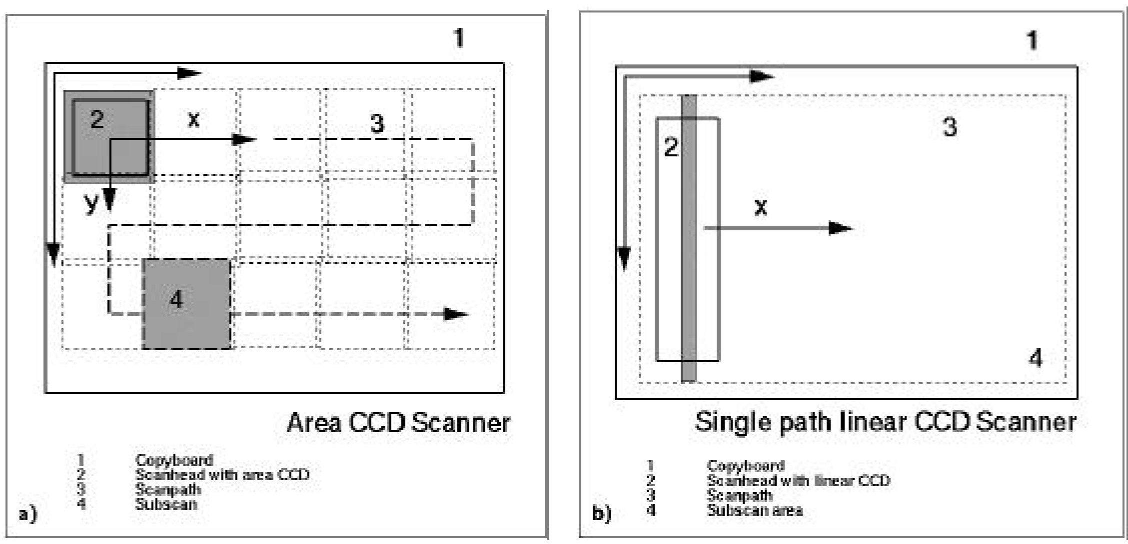
This îseamlessnessî across individual subscans has long been considered impossible to achieve, and was the reason why flatbed scanners were for a long time unable to compete with the very high resolution drum

[2] Designed by Vexcel Imaging GmbH (VIG) in Graz, Austria. Manufactured by Wild-Austria under contract for VIG.
[3] This technology is implemented in the VX-series of scanners of Vexcel Imaging Corporation in Boulder, Colorado.

scanners operating at resolutions of 5000 dpi and higher. However, as we will demonstrate in this paper, the novel UltraScan5000 is capable of matching the subscans into seamless large images, thereby eliminating one of the last advantages that drum scanners may have had.

2.4 Geometric Resolution

The geometric resolution of a scanner is defined by the optical path which maps each CCD-element onto the production image. The quality of that projection system, thus of the optical lens of the scanner, combines with the eveness of the movement of the scanhead along its path and the readout of electric charges from the CCD-device to accomplish a ”native” geometric resolution or pixel size in along-track and across-track directions. This in turn is modified by electronic averaging and software functions to produce an output at different than the native resolutions.



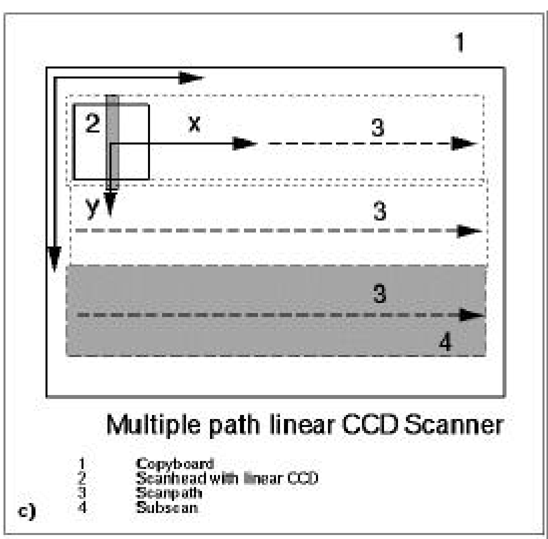


Figure 1: Three methods of flatbedscanning:
(a) With an area CCD;
(b) Single path scanning with linear CCD;
(c) Multi-path scanning with linear CCD.

3. ULTRASCAN5000, A NOVEL PHOTOGRAMMETRIC SCANNER

The principle of flat-bed multi-pass scanning with a linear CCD detector array is implemented in the UltraScan5000. It was first demonstrated in May of 1995 and 43 patent claims were granted in 1997. This represents thus the latest in high end film scanning. Figure 2 shows the device and Tables 1 and 2 summarize the system’s specifications. The UltraScan5000 covers a range of geometric resolutions from 50 dpi to 10,160 dpi, thus from 500 µm to 2.5 µm per pixel, and thereby covers a total scan area of about 13” by 18”.

The scanner is currently equipped with a Kodak KLI6003 CCD detector array with 3 * 6000 elements. There exist two native optical resolutions by means of two positions of the optical lens. These two optical resolutions are at 5000 dpi or 5 µm per pixel and at 868 dpi or 29 µm per pixel. They lead to two different native image scales which are being used to optimize the throughput at low geometric resolutions, and offer a useful tradeoff between geometric and radiometric resolutions versus throughput. Thus a pixel size of 15 µm might be achieved by down-sampling from the native optical resolution at 5 µm, or by up-sampling from a native optical resolution of 29 µm per pixel.

Figure 2: The novel UltraScan5000 multi-pass flatbed scanner with geometric resolutions ranging from 50 dpi to 10,180 dpi or from 500 µm to 2.5 µm per pixel, based on native optical resolutions of 5000 dpi (5 µm per pixel) and 868 dpi (29 µm per pixel).

Scanner Unit

Format: A3+ (280 mm x 440 mm @ 5080 dpi, 330 mm x 440 mm @868 dpi).
Optical Resolution: 5080 dpi or 868 dpi, user-selectable.
Geometric output resolutions continuously selectable between 10,160 dpi and 50 dpi.
Geometric repeatability: better than ± 1 µm.
Geometric accuracy: better than ±2 µm at 5080 dpi.
Density range: 3.4D.
Radiometry: uniformity and accuracy better than ± 1 DN at 8 bits.
Transmissive and reflective light, user-selectable.
One-pass color at native 3 x 12 bits, internal use of 3 x 16 bit per pixel.
Color, grayscale or line art, user selectable.
Negative black&white and color scanning.

Accessories

SCSI-2 connection to the computer host. Cabling.
Manuals (installation, user, training, support). Job sheets for precision scanning.
Calibration targets. Miscellaneous other accessories.

Software

Graphical User Interface GUI for Windows NT.
Various output formats (TIFF, RAW, EPS, DCS, SCITEX).
Output pixels at 8 or 16 bits per color separate.
Operating software for the controller unit (host computer).
Full color capability.
Support for scanning of negative originals, both black and white and color.
Photogrammetric support software with special on-line geometric calibration.

Computer Host

Compatible with Intel-PC, Power-PC and DEC Alpha-based Personal Computers.
Operating system Windows NT.

Table 1: Manufacturer’s description of the UltraScan5000’s capabilities.

PIXELSIZE µm	COLOR minutes	GRAYSCALE minutes
5.0	108	50
8.5	82	49
10.0	29	18
12.5	25	18
20.0	10	6
25.0	8	6
30.0	5	3

Table 2: Throughput for 23 cm x 23 cm Film (DEC-Alpha 433MHz, 128 MB Ram)

During scanning, the scanhead is being moved by means of stepper motors and precise lead screws. The direction of motion is always the same to minimize deviations of the scanhead path from its calibration.

The illumination serves for both transparent and opaque material using two different lamps, one mounted on the scan head for opaque originals, the other mounted over the scan surface and moving along with the scan head. To eliminate the unwanted effects of ambient lighting on the scanning result, there exists a cover that can be closed during the scanning operation. To further improve the radiometric performance of the system and to achieve the highest possible radiometric accuracy as well as range of densities, the sensing element is being cooled at all times to a specified temperature. This concern for radiometry is of particular value when one needs to scan negative originals where the subtle differences in dark areas of the object are mapped into bright areas on the negative.

Color is the strong suit of the device. Color images are being scanned in one single pass, thereby basically offering a throughput that is similar for black-and-white and color originals. Color management to deal with the scan results is an integrated component of the system.

To ensure that the resulting images are not only seamless, but also maintain a high geometric accuracy, the UltraScan5000 employs a number of geometric calibration procedures, both off-line in the factory, as well as on-line as the scanning process is active.

4. TWO-STEP CALIBRATION

In order to ensure sub-pixel accuracy when scanning images, the UltraScan5000 employs two separate calibrations. They are designed to model the effects of the scanner’s optical system and of the path of its moving scan-head so that its repeatability translates into absolute accuracy.

4.1 Off-Line ”Factory Calibration”

The first step of this calibration method is applied in the factory and will be repeated at the application’s site from time to time. It calculates initial geometric parameters of the scanner to transform each CCD-pixel from the internal coordinate system into a unique and well defined image output coordinate system. This first calibration step employs a calibrated reseau pattern which is being scanned and produces a dense field of two-dimensional linear transformation vectors (Figure 3). These vectors are computed in a comparison of the known positions of each reseau mark and the assumed position of the scan-head, and thus of the input digital image of the same reseau mark. The computation of the center of each reseau mark in the scanned image uses a method proposed by Trinder (1989).

Experimental results show that the scanner's optical and mechanical elements remain rather stable and, if unchecked, produce repeatable geometric deformations that therefore can be modeled by means of a factory calibration. While these parameters do remain stable over a long period of time, they might change as a result of shock, or of time. Therefore the scanner is being delivered with a calibration pattern so that a user can repeat the factory calibration at any time in the field and also verify that the calibration status is satisfactory. This factory calibration is sufficient to guide the procedures that assemble the individual subscans into a seamless array. The factory calibration also offers an absolute accuracy that is sufficient for most photogrammetric applications, for example the relative and absolute orientation of individual stereo models, the automated stereo matching for DEM generation and the creation of ortho-photos.

4.2 On-Line Calibration While Scanning

However, due to thermal changes and some mechanical reasons, there exist some small changes in the geometry of individual subscans, most notably the potential for an unknown offset of an entire subscan. This can be in the range of several micrometers. To ensure that these uncertainties are being removed during scanning, the UltraScan5000 operates with a photogrammetric on-line calibration refinement. It is based on the use of a so-called ”job-sheet” with reseau marks outside the actual scan area. The original photogrammetric photograph to be scanned is mounted on the job sheet and submitted to the scanner for digitization. The scanner collects pixels not only of the production image, but also of the area adjacent to the photograph, thereby scanning also the reseau marks. They are being recognized automatically as each subscan gets collected, and any deviations between the known coordinates of the reseau marks and their pixel-derived positions will enter into the geometric transformation of the subscan as it gets converted to the output coordinate system.

4.3 Challenges

The reseau marks, also denoted as ”targets”, need to satisfy several requirements, as reported by Baltsavias (1994) and Seywald (1996). There is, for example, a need to use an optimum target diameter as a multiple of pixels. Since the scanner covers a wide range of resolutions, this requirement presents a challenge that has been met by means of a specific arrangement of reseau marks. They are automatically detected in the digital images using either the Least Squares Template Matching (LSTM) as proposed by Förstner (1986), cross-correlation or Trinder's (1989) centroid algorithm. An accuracy of about ± 0.1 to ± 0.05 pixels has been observed with these methods.

The calibration targets have up to 144,000 reseau marks to ensure that the factory calibration models the motion of the scan head across the entire format with sufficient detail and accuracy. The reseau grid is copied on film and is part of the standard accessories of the scanner.

A verification of the scanner's performance is based on an accurate reference target manufactured by Heidenhain (Germany). Figure 3 reviews some of the various calibration and verification targets for different pixel sizes.

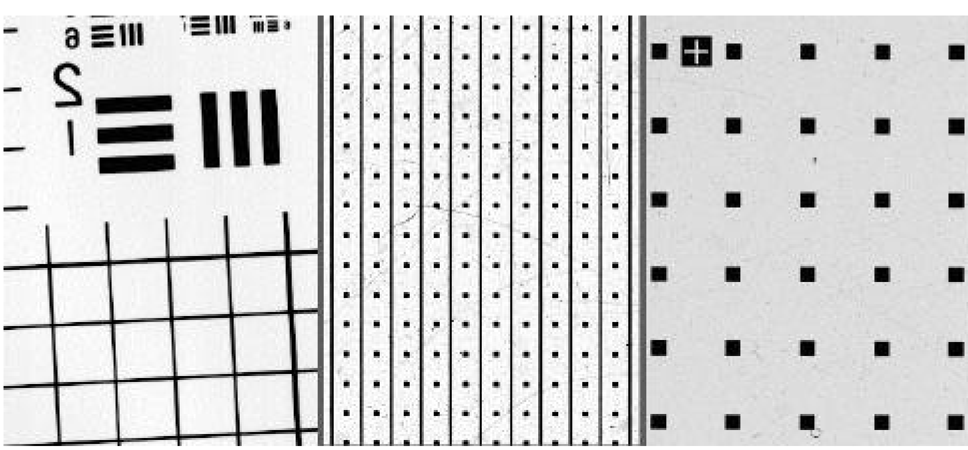


Figure 3: Digital images of targets used for calibration and testing at various different pixel sizes. Note that heavy use of some of the targets results in some scratches. Note also the uncompensated aliasing effect in the image of non-horizontal and non-vertical straight lines. For the purpose at hand, this is not relevant

4.4 Mathematical Formulations

The mathematical formulations for the use of the reseau marks are rather straightforward. Of course there exist several coordinate systems and numerous transformations, but in essence they all merge into a single geometric transformation process of each sub-scan. This receives inputs from (a) the factory calibration, (b) the on-line calibration and (c) the tie point matches found between adjacent sub-scans which are needed to ensure seamlessness. To satisfy the most demanding requirements of seamlessness, such tie points must be accurately matched to within a range of 1/20 of a pixel for the eye to not be able to recognize the transition from one sub-scan to the next. Figure 4 presents an example of an area where adjacent sub-scans abut, and it is evident that seamlessness is satisfactory.

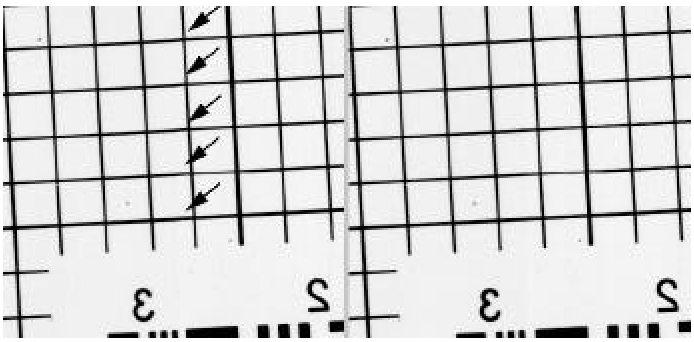


Figure 4: Example of two sub-scans shown in the left image side by side before accomplishing the match to remove any seaming effects. The right image presents the result after the match is completed. Note how mismatches are barely noticeable in the left image in an environment where an aliasing effect is also present.

5. SCANNING TESTS

5.1 Geometric Accuracy

In order to prove the reliability of the calibration method and the accuracy of the scanner we have carried out several experiments. For these tests a highly precise reference target was used and scanned. Table 3 summarizes the results from a series of tests employing the on-line calibration along with the factory calibration. The accuracy numbers refer to the positional, not the coordinate errors. Clearly one is in a range of accuracies that will be noticeably affected by limitations of the target. Table 4 presents the accuracy if the on-line calibration is omitted and only the factory calibration is being used. Note that without the on-line calibration the accuracies deteriorate to values commensurate with the accuracies advertised by other, more traditional photogrammetric linear array scanners that are currently on the market. Figures 5 (a) through (c) augment the presentation by means of vector diagrams of residual scanning errors.

It is relevant to realize that these tests were performed not with one, but with 3 scanners, and that they were repeated with varying pixel sizes. Note also that different targets were used for different pixel sizes to minimize the effect of the target size on the accuracy measure. This is likely also the reason why the errors in Figure 5(b) for the mid-size resolution of 20 µm seem to be poorer than both the values for 5 µm and those for 29 µm.

Scanner ID	Target ID	No. of Points	Online Calibration	Resolution dpi	RMS Position Error in µm
B1004	ICG3	1332	yes	5080	± 1.1
S2023	ICG3	1390	yes	868	± 1.4
S2023	ATAG2	1849	yes	868	± 1.5
S2023	ATAG2	7396	yes	868	± 1.9
S2013	HR	348	yes	5080	± 1.6

S2013	T17	1116	yes	1270	± 2.5

Table 3: Experimental results from scanning a reference target on the UltraScan5000 employing both the factory and the on-line calibration. Note that the rightmost column in this table reports the *positional* error, not the coordinate error that is smaller by a factor of about 1.4.

Scanner ID	**Target ID**	**No. of Points**	**Online Calibration**	**Resolution dpi**	**RMS Position Error in µm**
B1004	ICG3	1440	no	5080	± 4.0
S2023	ATAG2	1847	no	868	± 2.9
S2013	TAG22	1216	no	1270	± 2.9

Table 4: Geometric scanning accuracy of the UltraScan5000 when one ignores the on-line calibration. Note that the values approximate those reported for other, more traditional photogrammetric linear CCD array scanners. Again, this table reports *positional* , not coordinate errors which are expected to be at 1/1.4 of these values.

(a) σ_x= ± 1.2µm σ_y= ± 1.1µm (b) σ_x= ± 2.3µm σ_y= ± 1.4µm (c) σ_x= ± 0.9µm σ_y= ± 0.8µm

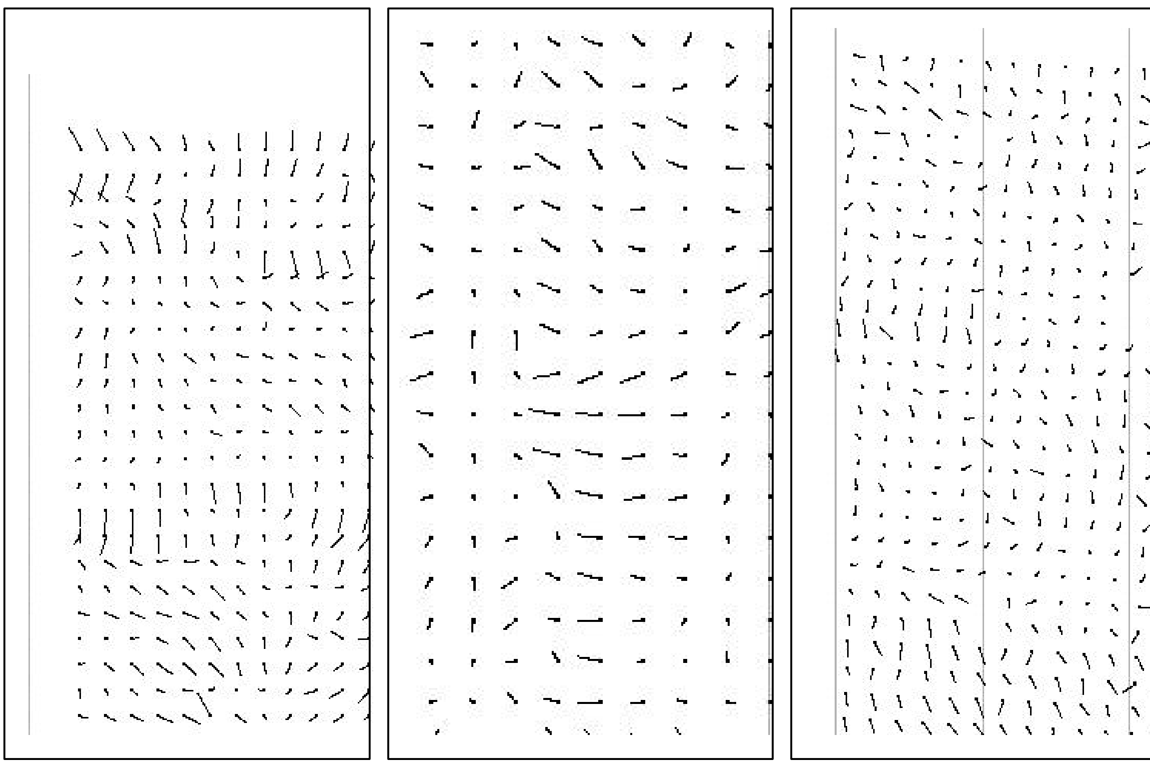


Figure 5: Sections of the scanned test targets with error vectors obtained by comparing the scans with the independently measured coordinates. (a) Pixel size of 28.8 µm or 868dpi and r.m.s. residual errors at ± 1.2 µm in x and ± 1.1 µm in y. (b) Pixel size of 20 µm and r.m.s. residual errors at ± 2.3 µm in x and ± 1.4 µm in y. (c) Pixel size of 5 µm and r.m.s. residual errors at ± 0.9 µm in x and ± 0.8 µm in y. The apparent irregularity at 20 µm with a larger residual error than at the coarser pixel size is likely an effect of the target used at that resolution, and the size of the target marks with respect to the pixel size that may affect the results of the centering algorithm.

5.2 Geometric Resolution

Figure 6 shows scans of the USAF resolution target at various pixel sizes. It serves to illustrate the systemís capability to actually resolve details as specified. At a given resolution expressed in ìkî µm per pixel, the Kell-factor predicts that a line pair will need k*2.8 µm to be resolved. At 5000 dpi, ìkî is at 5 µm, and a line pair would have to cover 14 µm or more to be resolved. It is evident from Figure 6 that the scans of the USAF target made with 5 µm pixels resolve the patterns in group 6, elements 1 to 3. Thess correspond to 64 lp/mm (6.1) to 81 lp/mm (6.3). According to Kell, 6.1 represents a pixel requirement of µm, 6.3 represents 4.4µm. Similar conclusions apply at the other geometric resolutions. For the example of scanning at 12.5 µm pixels, we find the limiting patterns to be at about 4.6, representing 28.5 lp/mm, and 5.1 at 32 lp/mm. This verifies that the scanner resolves the specified resolutions.

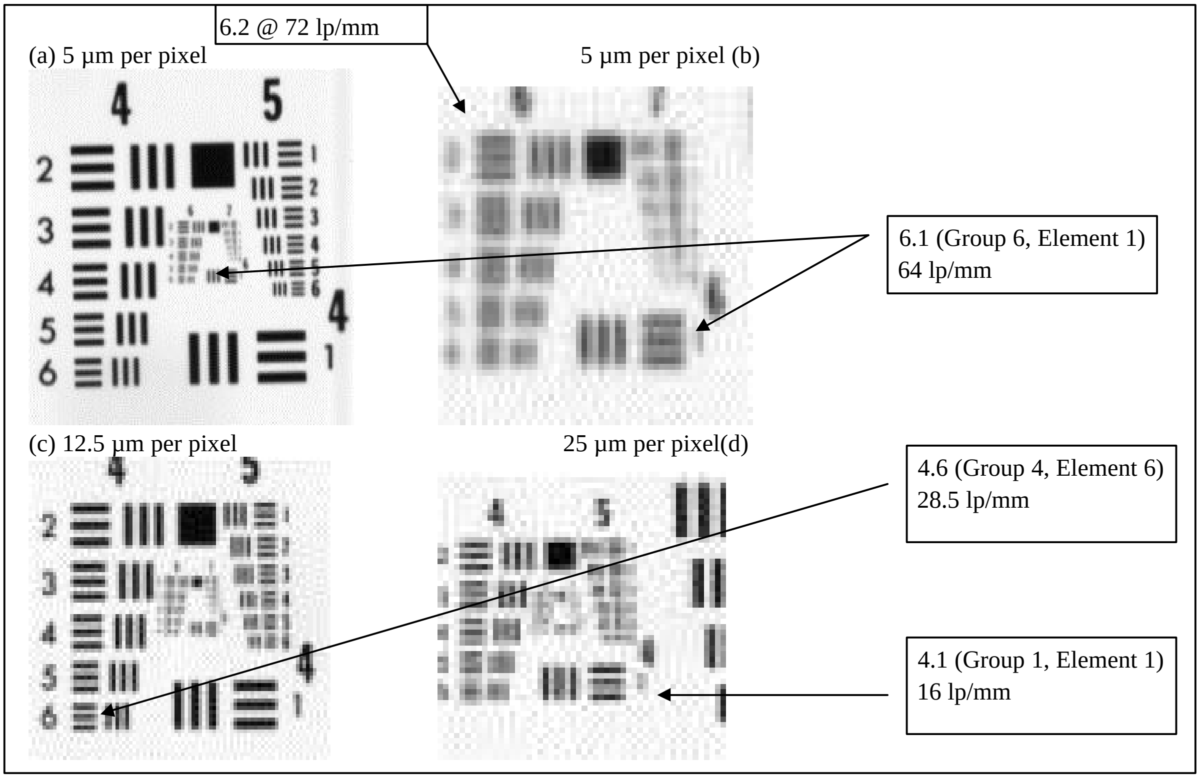
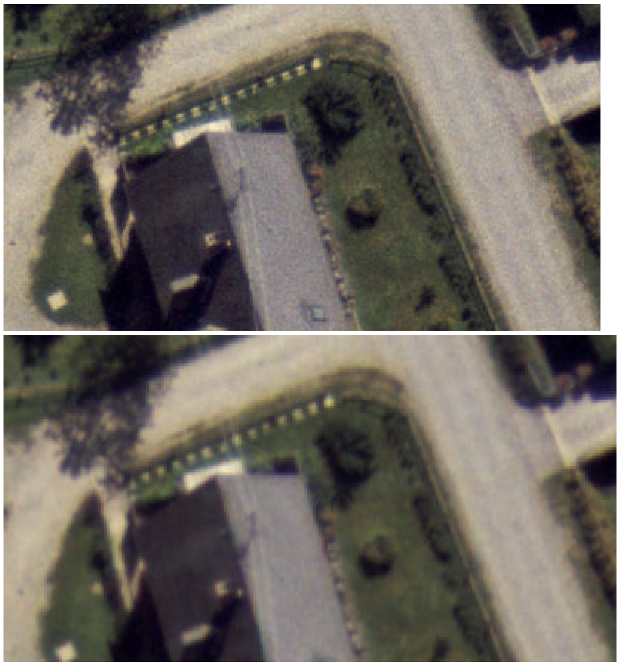


Figure 6: Scans of the USAF resolution target, in (a) at 5 µm per pixel, with (b) being an enlargement from (a) around the limiting patterns No. 6.1 to 6.3. Image (c) is scanned at 12.5 µm per pixel, (d) at 25 µm.

(a) (b)



(c) (d)

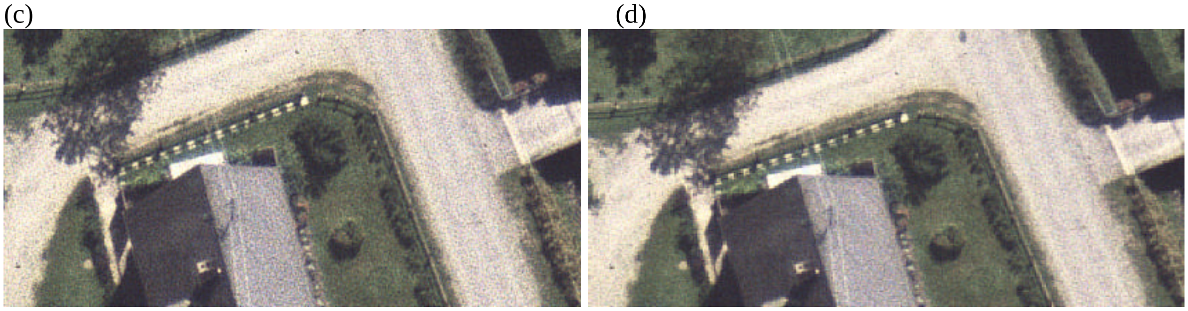


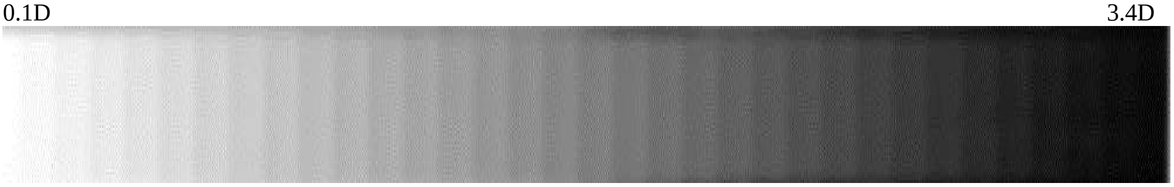
Figure 7: Scanning a color photograph at 15 µm pixel size. (a) Using the native 5 µm optical resolution. (b) Using the native 29 µm optical resolution. The differences are less noticeable after unsharp masking of both images in (c) and (d). Original scale 1: 9050, c = 210 mm, LMK2-camera (Zeiss Jena), AGFA Color Dia.

A unique capability of the UltraScan5000 derives from the fact that there exist 2 different native resolutions. Therefore a 15µm pixel resolution can be achieved by either computing this from the 5µm or from the 29 µm native optical resolution. Figure 7 presents an example. The differences apparent in Figs. 7a and b can be somewhat reduced with the application of an unsharp mask, as seen in Figs. 7c and d.

5.3 Radiometry

The Kodak gray wedge ST 34 spans a density range of 3.4D in 34 equally spaced increments. Fig. 8 is the result of scanning this target. It confirms the scanneris ability to resolve this large range of densities. An 8-bit presentation can illustrate this capability only marginally. Therefore the gray wedge is broken into several zones, each with a separately equalized histogram.

0.1D 3.4D



Part 1 Part 2 Part 3 Part 4 Part 5

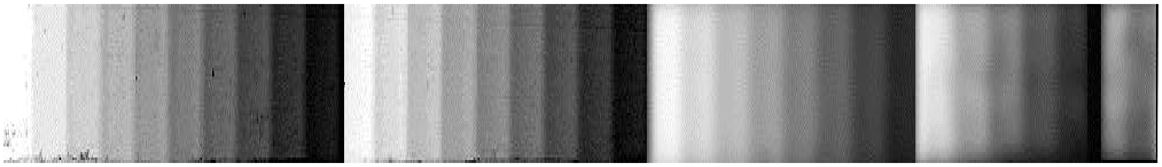


Figure 8: Scanning the Kodak ST 34 gray wedge on the UltraScan5000 and presenting the resulting density range of 3.4D in one piece (above) and in 5 separate parts to better visualize the fact that the entire range is being resolved into 34 individual densities.

5.4 Using the Scanner Operationally

Of course the routine use of scanned images is not to scan grid targets, but for automated DEM extraction, orthophoto generation and possibly the stereo-based extraction of object features. This involves an inner orientation of each scanned photograph, the computation of stereo parallaxes for a relative orientation, the absolute orientation, the use of stereo parallaxes for the subsequent conversion of these parallaxes into terrain elevations. Figure 9 shows two illuminated DEMs obtained automatically from two different scans of one single pair of aerial photographs at scale 1:40,000 from the US NAPP program. One scan used a pixel size of 20 µm based on the 5 µm native optical resolution, the other scan uses also 20 µm pixels, but derived from the native optical resolution of 29 µm. The DEM using the better basic optical resolution is crisper than the data set from the coarser basic resolution. Figure 10 shows a segment of each of the 2 scans of one aerial photograph where, analogously to Figure 7, the same pixel size is obtained from two source resolutions.

6. CONCLUSION

High precision document and film scanning is being achieved by multi-pass linear CCD-based flatbed scanning if the limitations of the mechanical unit can be properly calibrated. We present a novel photogrammetric scanning system, the UltraScan5000, and assess the quality of its output. We show that the system satisfies high geometric and radiometric requirements, including the ability to professionally deal with color sources.

The photogrammetric application has a unique concern for geometric accuracy. This is being accommodated by means of a two-step calibration. The first addresses the behavior of the linear motion unit and the related movement of the scanhead, including the parameters of the optical system. Such a calibration can be successfully applied in the factory, but can also be repeated at the customer site. Due to effects of temperature, potential

(a) From 20µm pixels based on 5µm optical resolution (b) From 20µm pixels based on 29µm optical resolution

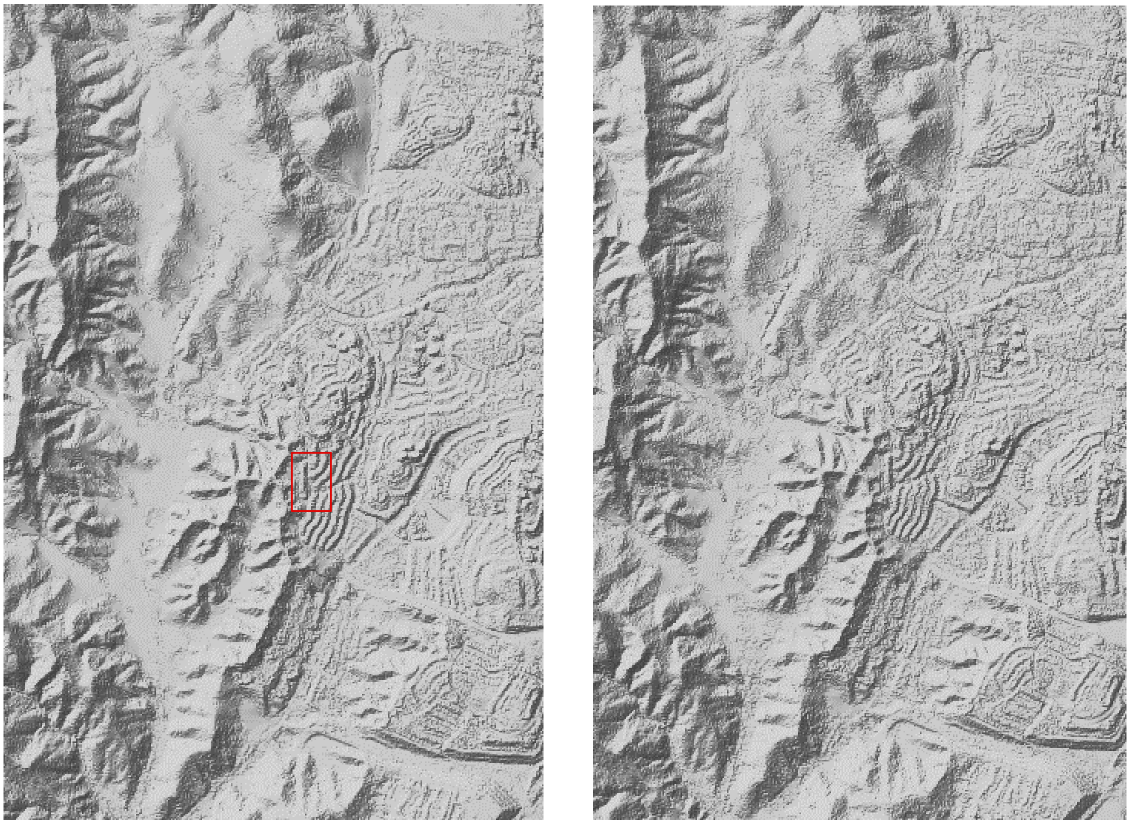


Figure 9: About 3 kms x 2 kms of a stereo-derived DEM is shown here, based on aerial photography at scale 1:40,000, scanned with 20µm pixels. In (a) these pixels are derived from the optical resolution of 5000 dpi or 5 µm per pixel, in (b) from 868 dpi or 29 µm per pixel. Note the increased crispness when the scan derives from the better source resolution. The outline of the area imaged in Figure 10 is marked in the left DEM.

(a) From 29 µm pixels (b) From 5 µm pixels

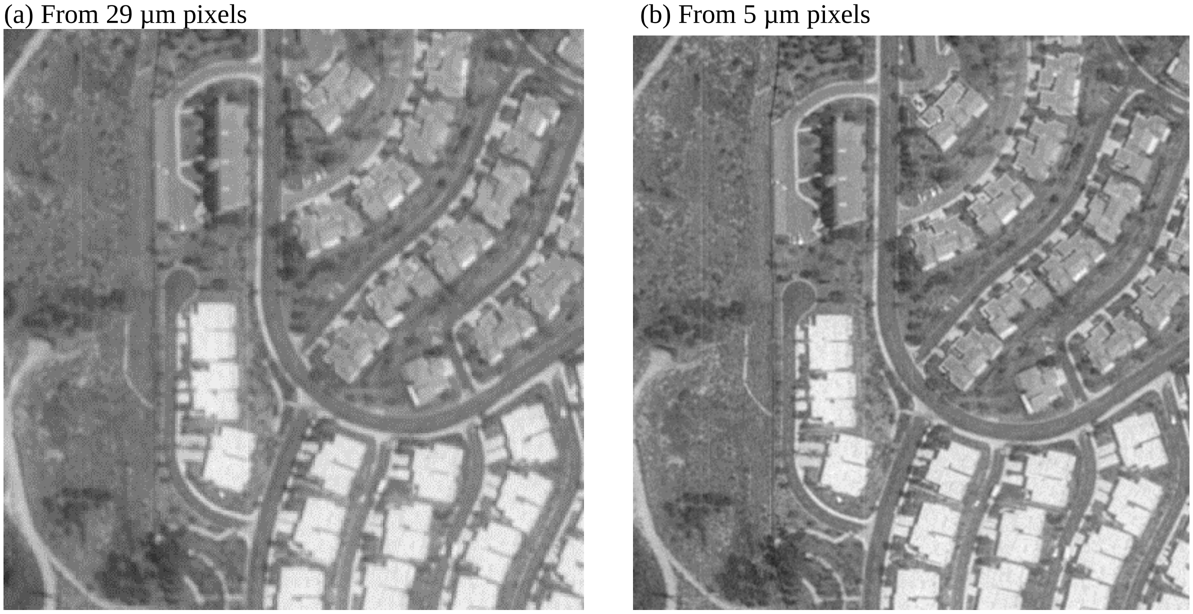


Figure 10: Segments of an aerial photograph used to create the DEMs in Figure 9. Scan resolution is 20 µm per pixel, but in (a), the pixels are obtained from the native resolution of 868 dpi, in (b) from 5000 dpi. Area is about 180 m x 180 m .

changes over time, the need to ensure the scan head's starting position and the need for absolute accuracies, one also needs to be concerned with geometric effects as they occur at the time of scanning. This basic principle has already been successfully used and demonstrated in an earlier scanner design, originally in the VX3000 and later the VX4000 scanners produced by Vexcel Imaging Corp. of Boulder, CO, using square array CCDs[4] (see Leberl et al., 1990a and b). While the earlier solutions were based on near-simultaneously, thus near-"on-line", imaging an "invisible" reseau, this is now replaced by another type of calibration without an invisible reseau, yet also operating fully (not "nearly") on-line also. We have shown that this method removes residual scanning errors in the range of 3 to 5 µm, and that it can improve the geometric performance into a range that is not easily verifiable since it reaches into the sub-micrometer range.

This paper illustrates the scanner's performance with test scans of reference targets for geometry, resolution, radiometry, and with real aerial photography as well as some DEM-generation from scanned aerial photographs. The results of our experiments have shown a density range of 3.4D, and remaining RMS error of the pixel coordinates of the digitized image in the range of ± 1 µm. These errors across large formats stress the limits of one's verification ability, and one becomes susceptible to small irregularities of the targets. However, one can nonetheless safely state that the accuracies will satisfy the most stringent requirements of photogrammetric scanning applications. The tests fully qualify the UltraScan5000 as an interesting and useful offering on the photogrammetric equipment market.

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[4] The VX3000/VX4000 designs were based on inventions by F. Leberl, founder of Vexcel Imaging Corporation in Colorado and Vexcel Imaging GmbH in Austria, and jointly with Ch. Jorde and M. Gruber, inventor of the UltraScan5000.