The VX-Series of interactive film scanners: film-based softcopy photogrammetry

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ABSTRACT

Softcopy photogrammetry's advent is a product of current advances in computer workstation technology and the low cost of image processing boards. Photogrammetric high resolution sensing remains, however, the realm of classical film-based photography. For softcopy-based digital photogrammetry to succeed creative solutions are needed to convert film to pixel arrays.

We describe a novel scanning concept that permits one to convert a full frame of metric photography into an array of 32,000 x 32,000 pixels, or it permits the interactive "grabbing" of windows of pixels with sub-pixel accuracy while supporting a software-controlled zoom range with minimum pixels of 8µm and maximum pixels of 170µm. At the heart of the new concept is the so-called "invisible reseau".

Implementation of this new concept is in the form of the VX-series of scanners. The concept is discussed, and performance characteristics of the VX-Scanner are subject to analysis. The issue of "optimal" scanning parameters in both geometry and radiometry is a concern. The benefits derived from an interactive zoom-based approach to scanning are being highlighted.

1. AERIAL PHOTOGRAPHY AND SCANNING

As computer technology rapidly reduces the cost of hardware capable of processing large arrays of images, the capability to create images for such processing is lagging behind. Electro-optical sensing is not promising to replace aerial photography in the near future. However, the rapid acceptance of digital image processing technology, the advent of the Geographic Information System, and the benefits of combining graphic information with a displayed image in a computer workstation create an impetus to provide technologies to convert conventional film imagery to a softcopy format.

Aerial photography is a very inexpensive source of information. Typically an aerial photograph can be obtained for a cost of $10-$40 depending on the number of photographs produced for one particular project and it may cover areas of more than 100 km^2. Therefore, aerial photography could be analogous to other ephemeral media such as newspapers; as soon as an aerial photograph has been taken and analyzed it becomes obsolete because there is no certainty that the information content of the photograph remains relevant for an extended period of time. Should a need exist to revisit the imaged ground area at some future time, it may be meaningful to create new photo coverage.

This basic premise holds true only if the value added to an aerial photograph by processing is minimal. However, aerial triangulation and ortho-rectification are types of processing which add value and cost to the photograph and therefore cause one to hold on to an obsolete photograph even though the information shown in the photograph has become incorrect.

We argue that conventional image scanning is also adding "value" to the aerial photograph that puts pressure on the user to rely on an aerial photograph beyond its useful life.

The need exists, therefore, for a solution to this dilemma by introducing a type of image scanning that is inexpensive and that supports the concept of photography as an ephemeral medium. For this to succeed, film scanning has to be decentralized and in the hands of the user rather than in a centralized service bureau. An approach that requires a service operation to scan photography inherently causes one to treat data "with respect" and not to discard the scan information after it is used. An approach is needed which does not penalize a user for "throwing away" the digital pixel array after its use.

2. THE INVISIBLE RESEAU FOR MENSURATION FRAME GRABBING

2.1 Scanning using square tiles

We are describing an interactive scanning concept which permits one to work with aerial photography in a computer workstation without any specific added costs for the scanning process other than the computer peripheral that is used to convert image areas of interest. The central element of innovation is the "invisible reseau" in conjunction with a square array-based digital CCD camera. We describe in this contribution the underlying technology and resulting capabilities of this innovative scanning concept. The concept has been implemented in the series of VX-film scanners which are currently being introduced by Vexcel Corporation (Figure 1).

We denote the method of digitizing a large area of film by means of a square CCD array by "mensuration frame grabbing" (Leberl et al, 1987). Typically the digitizing of a square window of imagery via a CCD array is denoted by "frame grabbing". A number of efforts have been made to base the conversion of film into softcopy medium on frame grabbing. This includes the use of a visible reseau (Luhmann and Wester-Ebbinghaus,1986; Lohman, 1986; Rollei, 1986; Rollei,undated), the use of multiple square arrays that are precision mounted (a 36mm slide scanner offered by Array Technologies, Inc.,undated) or a square array that is subject to precise motion, as in the implementation by Schafer Associates (undated).

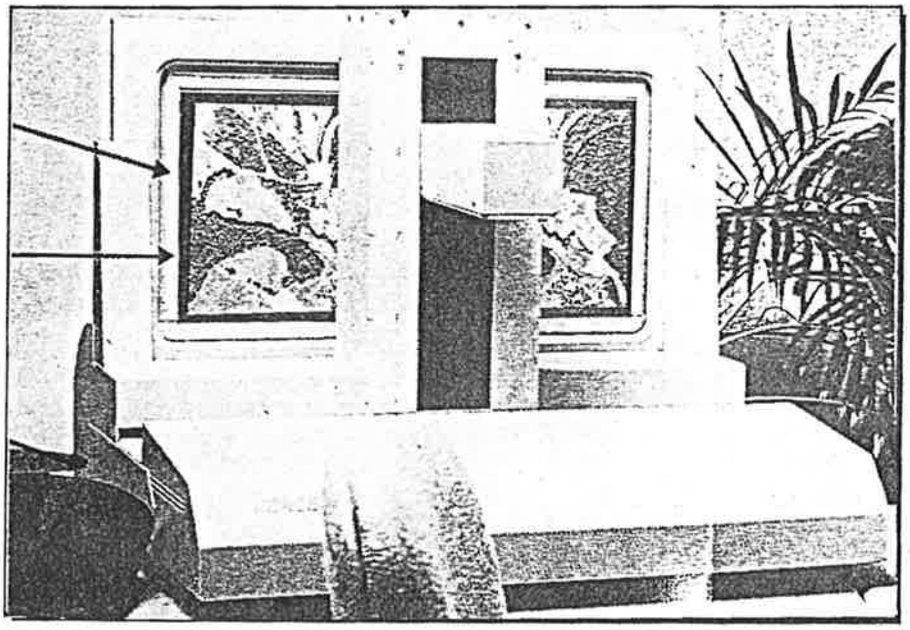

Figure 1: The VX3000 Color Film Scanner as a peripheral to an image processing workstation.

Frame grabbing is but one of three basic technologies currently in use for document scanning:

(a) A single light-sensitive dot collects the light that is transmitted through or reflected off an instantaneous field of view on a document; a pixel array is assembled by continuous two-dimensional motion of the instantaneous field-of-view over the document;

(b) A linear array of detectors simultaneously collects the light from many instantaneous fields-of-view and a two dimensional image is assembled by continuous linear motion of the detector array; individual linear "profiles" may need to be assembled into an array wider than the individual profile (Faust, 1989);

(c) A square array of detectors is used and collects light from a two dimensional array of instantaneous fields-of-view, while the CCD array is in a stationary position (frame grabbing). A larger array of pixels is assembled from the individual "tiles" or frames.

There are numerous design issues surrounding the choice of a particular technology. They all have in common that precision motion is necessary to assemble a large image from the individual direct observations obtained from either a single light-sensitive element, a linear array of elements or even a square "tile".

2.3 The value of an invisible reseau

Geometric accuracy, spatial resolution and format are closely linked to cost. Scanners of utility in photogrammetric applications need to offer a format of 23cm x 23cm, pixel sizes of 10µm and larger, and a geometric accuracy of perhaps 0.2 pixels (for precision mensuration, and for high quality stereo-correlation). This is a requirement which so far has only high-cost solutions. Hope to reduce the cost of photogrammetric scanning exists if precise mechanical motion can be avoided. But the current scanning concepts not only are expensive, they also limit the functionality of the scanning device in terms of choices of zoom factors or pixel sizes and in the ability to perform the digitizing process in an interactive mode rather than a batch mode.

The use of the "invisible reseau" permits one to avoid high mechanical accuracy and provides the freedom to scan with variable zoom and switch between, on one hand, the operation of a hybrid light table, and on the other hand, the use of batch scanner.

2.4 Use of the invisible reseau

How is the invisible reseau being used? The film emulsion touches the reseau. In a scanning process, a camera is mechanically moved over the document and under software control is placed over a selected area of the film (Figure 2). The accuracy of this placement can be fairly coarse. An image is made of the reseau grid, whereby the film itself is not illuminated and only the reseau is visible. This image is analyzed and reseau grid intersections are being found by image pattern recognition. This allows to precisely place the camera and the direction of the optical axis, it permits one to account for lens distortion, etc. Subsequent to this analysis, an image is now made without the reseau visible, but with the film area being illuminated. This leads to a temporary pixel array representing a " tile" of imagery. This tile can be transformed via the known reseau locations into the output format. In a process of "tiling" the individual tiles are assembled into a large seamless pixel array. The reseau itself is not cluttering the image.

In order for this process of tiling to be successful, the use of the reseau has to be very precise. The design goal is to abut adjacent tiles to an accuracy of about ±0.1 pixels.

If a black and white image is being scanned then the digitizing of each reseau image is followed by digitizing of one black and white film window. In the event of a color image, the digitizing of the reseau window is followed by the digitizing of three color windows in red, green, and blue through appropriate dichroic filters.

In principle we have a fairly simple concept for scanning that permits the creation of a system that has low mechanical costs and translates mechanical requirements into software solutions. We therefore deal with "software-leveraged hardware". However, it order to be a successful system, the software needs to address the reseau recognition, the assembly of individual tiles into a seamless pixel array, and it needs to deal with all the issues of light, light fall-off, evenness of illumination in space, time and color, and variable light sensitivities of the individual CCD elements.

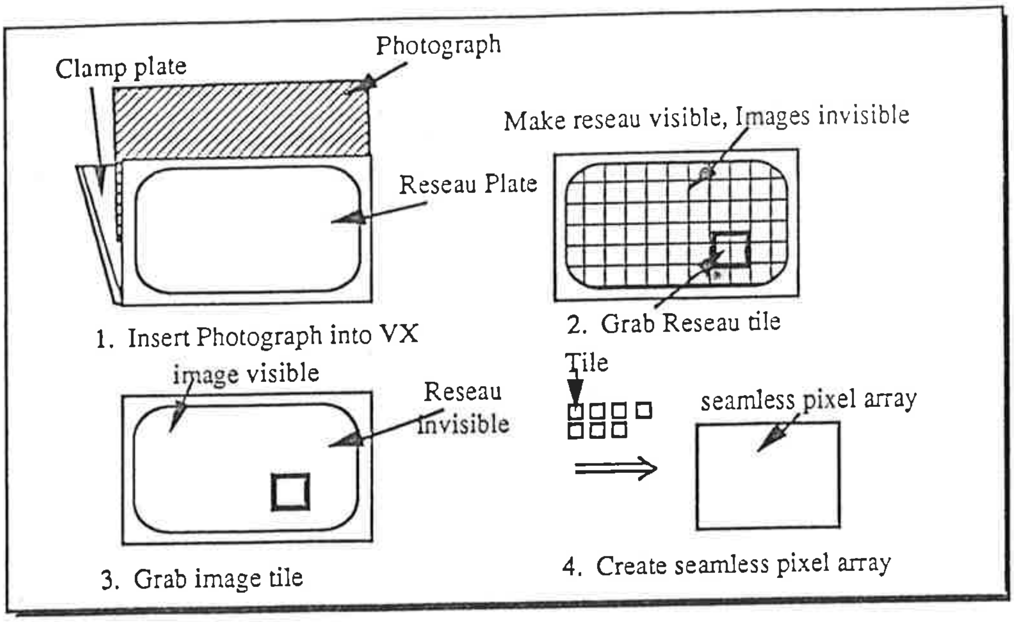

Figure 2: Concept of the invisible reseau for use in Mensuration Frame Grabbing

3. CAPABILITIES OF A SCANNER WITH AN INVISIBLE RESEAU

3.1 Batch-type scanning

A scanner such as the one described here can be used in the traditional way as a batch-type film to pixel conversion instrument. The user will initiate a scan by selecting the proper light levels, the proper pixel size, and the proper area to be scanned. The instrument then autonomously will go through the area and digitize the individual tiles and assemble them into a seamless array.

3.2 "Interactive scanning"

The capability exists to use the device as an "interactive" scanner. The user may work on an image processing application that requires particular windows of image data. Rather than going to a disk file and selecting the appropriate data window from that file, a command is sent to the scanner which subsequently moves to the desired image area and selects that area at the desired pixel size for instant digitization. This is the prototypical application of "mensuration frame grabbing". "Mensuration" is entering into this process because the image window that has been digitized is geometrically made to fit the overall pixel coordinate system through the use of the invisible reseau. This particular application of course would lend itself ideally to a workstation operating Geographic Information System software. Instead of having a fully digitized aerial photograph as an information layer in the GIS, the user has access to the film image and grabs the appropriate area at the appropriate magnification whenever needed. The use of very large real-time disks is thereby avoided. Note that the data quantity for a color image at full resolution might well be 2.5 gigabits at 8µm per pixel. Most current image processing systems would be overwhelmed by a requirement to handle 2.5 gigabits of data for a single image in near real time.

The "mensuration frame grabbing" approach offers a solution to the use of softcopy data at high resolution without having to actually administrate large digital data quantities.

3.3 Comparator mode

A third approach to employing this innovative scanning concept is the one implemented in systems such as AutoSet (Fraser and Brown, 1986; GSI, undated) or the Rollei RS1 reseau comparator (Rollei, undated). In those applications, the aim is not to digitize an image so that interactive work can be performed on the image, but the purpose instead is to measure the coordinate of a particular feature, typically a signalized point, and automate the measurement. In the current context, the invisible reseau device can be used as a comparator and coordinates of features can be measured on the film placing a measuring mark over an object of interest and reading the pixel coordinates. The pixel coordinates are measured first in a local coordinate system within an image tile, are then transformed via the reseau intersections into a table or photo-coordinate system. If the image is not used for analysis, but merely for the limited purpose of measuring specific coordinates, then the "invisibility" of the reseau is of lesser concern.

3.4 Continuously variable zoom

A very significant capability of a scanning process based on an invisible reseau is one's ability to employ a continuously changing zoom. Because the geometry of each pixel is derived from the reseau in the plane of the emulsion, the precise magnification of the optical system needs not to be known and the scale can be determined from the reseau image. This permits one to arbitrarily change the magnification. As the pixel array is digitized one transforms the grabbed image window into the proper location and to the correct pixel size even though the optical system may have had a slightly different pixel size. Systems that need to rely on mechanical accuracy have difficulty in changing the optical system's magnification arbitrarily because of the effect of those changes on the direction of the optical axis and the optical characteristics of the lens system.

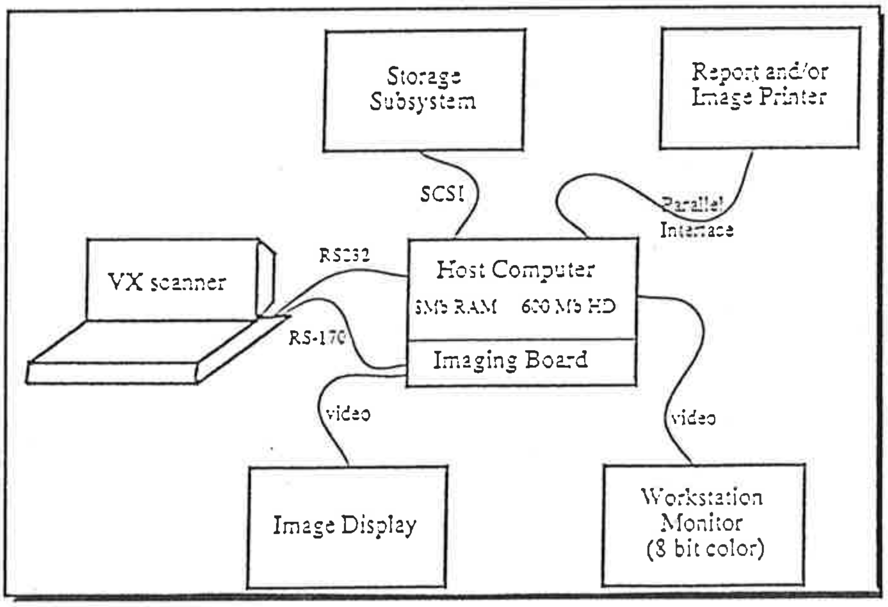

Figure 3: Example workstation hardware configuration for the use of the VX-Scanner

4. THE VX-SCANNER

Table 1 presents an overview of key technical capabilities of the VX-Scanners. Figure 3 is an example configuration that an individual user may employ. Note that an image processing computer will employ the VX-Scanner as a peripheral. Depending on the specific application a configuration like the one sketched can be used as a batch scanner or as an interactive image processing system into which the relevant photo elements are digitized on demand. The geometry is entirely controlled by the reseau. The only violations of high accuracy can occur if either the reseau were recognized with an error or if the film plane were not in the plane of the reseau.

The design and implementation of the system such as the one described here requires intensive concern for lighting.

The illumination and lighting conditions for the scanning system are calibrated in large part by software. The approach to calibration is to assess the capabilities of a particular component of the scanner and to correct for any deviations from the ideal by appropriate software. This is only feasible where the instrument is predictable and consistent.

Consistency in the behavior of all lighting, camera and lens characteristics is therefore of prime importance. This has been accomplished in a satisfactory manner so that the error in gray value due to illumination variations is hidden in the noise as specified in Table 1. Figure 4 is an example of measurements illustrating the variations in lighting as a function of time and as a function of wavelength (red, green, blue). It is illustrated that these variations are within the noise level with the root mean square value of about 1/DN.

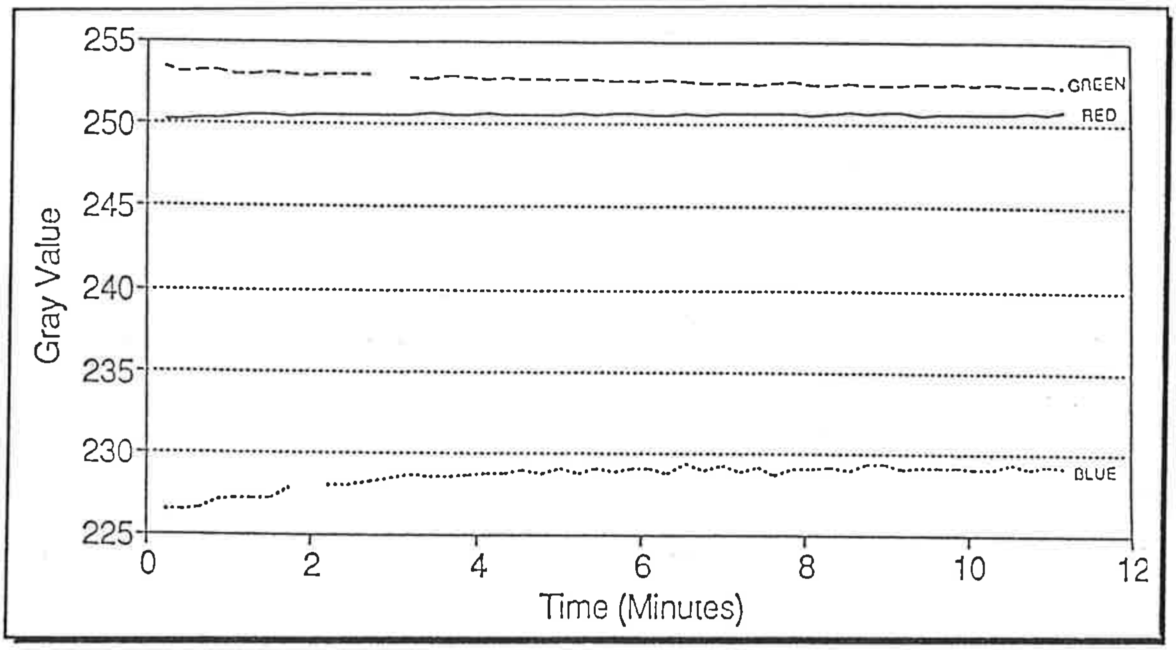

Figure 4: Assessment of the radiometric stability of the VX-Scanner by observing red, green, and blue color for a period of time and over a large scan area. The camera is moved and gray values are changed for each color and then the gray values are plotted for each color to demonstrate stability.

5. APPLICATIONS ISSUES

5.1 Batch scanning

Since batch-type scanning is being widely used it is well understood. In the particular case of the VX-Series an output format is generated that contains routinely an overview image for quick inspection and quality control. Various output formats for the image can be obtained for subsequent use in areas that go beyond photogrammetry, such as the Graphic Arts.

5.2 Interactive scanning to replace a large digital real-time disk

The interactive approach to digitizing may represent the capability that is most relevant to photogrammetric applications. For stereo correlation and proper identification of mapping detail, the full resolution of a photograph needs to be exhausted. This is currently prohibitive if based on batch scanning. In the stereo case, two 30,000 x 30,000 pixel arrays would have to be processed. This would imply that two entire images are scanned onto a magnetic medium and then are used to extract from the large digital image the data windows needed for particular applications at a particular moment.

Computer Interface: • Control software under UNIX®/C • User interface in X Windows™ • RS 232 (commands), RS 170 (video) *Optical/Film:* • Light source: Cold cathode Variable intensity (SW controlled) • Image detection: CCD camera Fixed focal length lens • Optical system: 21 to 1 magnification range 2-axis zoom • Density range: 3.0 *Accuracy:* • Radiometric: ±1.0 to ±2.0 DN (Digital numbers) • Tiling (sampling): Better than 0.5 of the pixel size • Positioning: 0.1 of the pixel size	*Resolution:* • Spatial: Variable 3,250 dpi (7.9μm) to 150 dpi (165 μm) • Spectral: Black-and-white with full 8-bit (256 gray levels) 24-bit color capabilities *Data Acquisition* • Data frame format: 245,000 pixels/tile • Data rate: Between 0.5 sec/tile and 5 sec/tile *Mechanical:* • Viewing and scanning area: 10" x 20" (254 mm x 508 mm) • Maximum instantaneous field of view: 3.15" x 3.15" (80 mm x 80mm) *Software Calibration* • Autosizing • Autofocus • Autopositioning • Autocalibration for gray balance *Physical and Environment:* • Dimensions: 27"W x 28"D x 21"H (686 mm x 609 mm x 533 mm) • Weight: 159 lbs. (72.3 kg) • Desktop configuration for standard office environment • Power requirements: 120V, 60hz, or optionally 220V, 50hz

Table 1: Specifications of the VX-Scanner

The VX-type scan will be advantageous since it substitutes for the digital pixel array on a disk the analog film in the VX-Scanner. Should a particular window be desired to appear on the interactive display screen or be subjected to a stereo correlation process, then the scanner will assemble the relevant pixels on the fly. This avoids the need for large disks with very fast access but still keeps the image available to the user of digital data. The VX-Scanner can at this time be considered a substitute for digital disk.

5.3 A need for the digital orthophoto?

Of particular concern may be the use of raw image windows in the context of Geographical Information Systems. One commonly assumes that a digital orthophoto should be produced for use with a GIS. But images will not have to be rectified when the image window comes up on the screen and geographic information is superimposed (Figure 5). Such a concept has amply demonstrated its value in an implementation with the City of Denver. Instead of creating a digital elevation model and a digital ortho-photo, it is feasible to transform the GIS window into the geometry of the image and display both jointly on the screen.

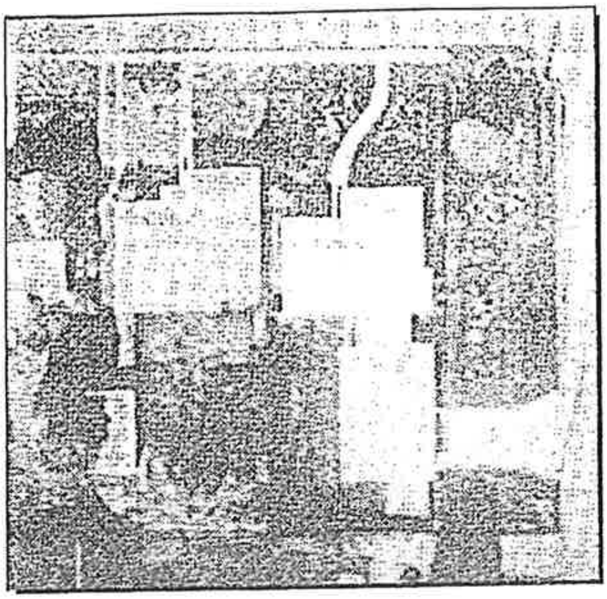

Figure 5: Superimposing GIS and Unrectified Image Windows

Since the coordinate relationships between the unrectified image and GIS are known at all times from a resection in space, any work with the data on the screen would be in the image coordinate system but would be permanently stored in the GIS in the object coordinate system. This is not to say that the digitized image window could not be ortho-rectified if a digital elevation model is available. But in light of earlier remarks, it may be advantageous to do the faster and simpler task of projecting the graphic information into the image coordinate system than to resample the digital pixel array of the image via a DEM into the geometry of the Geographic Information System.

5.4 Scanning directly into an image or epi-polar coordinate system

In the event of a photogrammetric application, the choice of coordinate systems for the pixel array can be made in such a way that the pixels are being scanned directly in an image coordinate system defined by the fiducial marks. This is not available in batch scanners that are currently on the market. In the VX case, four or more fiducial marks can be at first visited and the fiducial coordinates can be defined in the coordinate system of the reseau. Subsequently the coordinate system for the output image can be selected to not be the reseau system but instead the system defined by the fiducial marks.

This may be of value to a digital stereo correlation system that has as its front end the VX-Scanner holding two photographs. The homologue image windows on the two images are being grabbed sequentially and are submitted to the matching process. The correspondence between the image tiles can be established from a relative orientation of the two photographs in a preprocessing effort. This would also permit one to assemble the tiles into an epi-polar coordinate system. While we have not implemented such a system at this time, we expect that VX-users will develop such capabilities for photogrammetric use.

5.5 Scanning for a digital orthophoto

Similarly, of course, one can create the ortho-photo in an interactive scanning process. Rather than doing a batch scan of an entire image and holding that scan on disk, one could go window by window and transform each of those windows via a DEM into the output segment of the resulting ortho-photo. Again such a system has not been implemented at this time, but the value of the VX-concept for this application is obvious.

6. CONCLUSION

We have introduced a film scanning concept based on a partially visible and invisible reseau in the plane of the emulsion of a film image. Scanning is based on the use of a CCD square array in the focal plane of the optical system. An image is scanned by moving a camera in a checkerboard pattern over the image, stopping it at specific locations, grabbing the image segment and assembling the image segments into a seamless array of pixels.

While the concept is straightforward, its implementation depends on the successful ability to position the camera accurately via the reseau in an automated manner, to assure invisibility of the reseau to avoid artifacts in the scanned pixel array, and in the successful correction of all variations, either spatially or temporally, of both a geometric or radiometric nature.

We have solved the technical challenges of actually implementing a commercially available solution and offer a product for users who wish to be able to scan with high geometric accuracy, radiometric fidelity, at low cost, thereby having interactive control over the quality of the scan.

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