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Digital Orthophoto Production Using Scanning Microdensitometers*

The software system creates orthophotography from digital elevation models (DEM's) and the aerial film negatives by using a microdensitometer as the input/output device.

ABSTRACT: *Scanning microdensitometers are gaining widespread usage in photogrammetry because of their versatility as a precision comparator during both the input and output phases of analytical and digital photogrammetric processing. The intent herein is to describe a software system which creates orthophotography from digital elevation models (*DEM's*) and the aerial film negatives by using a microdensitometer as the input/output device.*

A DEM *and photographic model orientation parameters (either from a digitized stereoplotter or from scanned negatives which have been correlated using digital image correlation and processing techniques) provide the basic input. From the known model coordinates and camera orientation parameters, the* x *and* y *image coordinates of either photo in the stereopair are computed for each interpolated model point. The densitometer is then used to extract the film density at each image point corresponding to each model point. These film densities are then rewritten by the densitometer in corrected orthographic positions onto orthophoto film at any convenient scale. Normalizing, relief shading, contours, grid systems, and other image processing modifications can be superimposed to enhance or modify the final orthophoto product.*

INTRODUCTION

THE RAPID EVOLUTION of photogrammetric instrumentation toward automation with digitized input, manipulation, and output devices is providing photogrammetrists with more versatility, faster production modes, and better products. Tremendous technological gains have been made with precision mono-comparators, analytical stereoplotters, and orthophotographic reproduction units.

The scanning microdensitometer is an instrument with the potential of merging the capabilities of each of these instruments. These units are precision comparators with encoders and computer driven servomotors to drive the optical train anywhere on the imagery. At any location the image density can be extracted and converted to digital form. Conversely, digital values after the appropriate image processing (filtering, enhancement, annotation, classification, rectification, and transformation) can be converted to analog signals which are used to recreate the image onto unexposed film.

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This paper discusses one application of the scanning microdensitometer in photogrammetry, the creation of orthophotographs. The concepts are developed and the software which has been programmed is explained. Other potential applications also are explored. The testing of the system is ongoing and the results are yet incomplete. A second report assessing the overall performance of the proposed system will be written to complement this paper.

OBJECTIVE

The intent of this project was to develop a software interface between an unrectified aerial photograph and its corresponding digital elevation model (DEM) for the purpose of creating an orthophoto on a scanning microdensitometer. The program begins with the measured x and y coordinates for the fiducial marks and control points as input and ends with a magnetic tape of image space coordinates, corresponding to interpolated ground points. These image coordinates, when scanned in non-orthogonal fashion, will represent true ground positions when rectified and rewritten onto orthophotographic film.

It should be noted that previous efforts to create orthophotographs from unrectified imagery involved orthogonal model space scanning of the unrectified imagery and movement of either the transfer optics, the original imagery, or the orthophotographic film plane to complete the rectification during transfer. This leads to the overlaps and underlaps in the resultant products and/or additional hardware to complete the task.

With the system described herein, higher spatial resolution is obtainable since the rectification process is already complete when the imagery is first scanned and no resampling or averaging is required. This concept is further explained in the section which follows.

CONCEPTS

The diagram shown in Figure 1 depicts the steps necessary to locate the corrected and rectified image point coordinates representing ground points at intervals consistent with the desired output scale and resolution. Briefly, the software has been developed to operate in the following manner.

The fiducial marks (three to eight) and control points (minimum of three combined horizontal and vertical) are measured using the scanning microdensitometer. These coordinates, in conjunction with the camera calibration parameters, provide the input necessary to transform densitometer coordinates (affine transformation) into image coordinates in the photographic fiducial axis system and to correct for differential shrinkage or expansion of the film negative.

These coordinates are then optionally corrected for any other systematic distortions which seem appropriate according to the accuracy requirements. Once the refined coordinates have been computed, corresponding ground control coordinates of the measured image coordinates are input and used to solve the photograph's perspective absolute space orientation. A least-squares solution is employed to include any number of redundant measurements and assess the quality of the solution matrix.

The DEM is then interpolated to produce coordinated ground point locations at required intervals. Rectified image coordinates corresponding to these ground point locations are then computed using the inverse condition of collinearity from the known orientation parameters of the scanned photograph.

The rectified image coordinates are then modified by reintroducing any distortion effects which may have been eliminated by the stereoplotter during the creation of the DEM. (Here it must be realized that the microdensitometer will scan the unrectified photo complete with distortions and, therefore, should be driven accordingly.)

The final step in the software package is to transform the modified, rectified image coordinates back into the arbitrary microdensitometer system. The film negative can then be scanned non-orthogonally using these coordinates so that a serial orthogonal playback would produce planimetrically correct orthophotos.

The development of the FORTRAN coding to complete this task is amplified in the PROGRAM section contained herein. Before expanding upon the programming concepts, a brief description of the microdensitometer and DEM being used is offered for sake of completeness.

MICRODENSITOMETER

Several microdensitometers (with modifications to increase throughput) being manufactured today are capable of orthophotographic reproduction. One such device is described to indicate the salient features.

The Perkin-Elmer Corporation manufactures the PDS Microdensitometer Data Acquisition System (Horton, 1978) which can sample and record spatially distributed in-

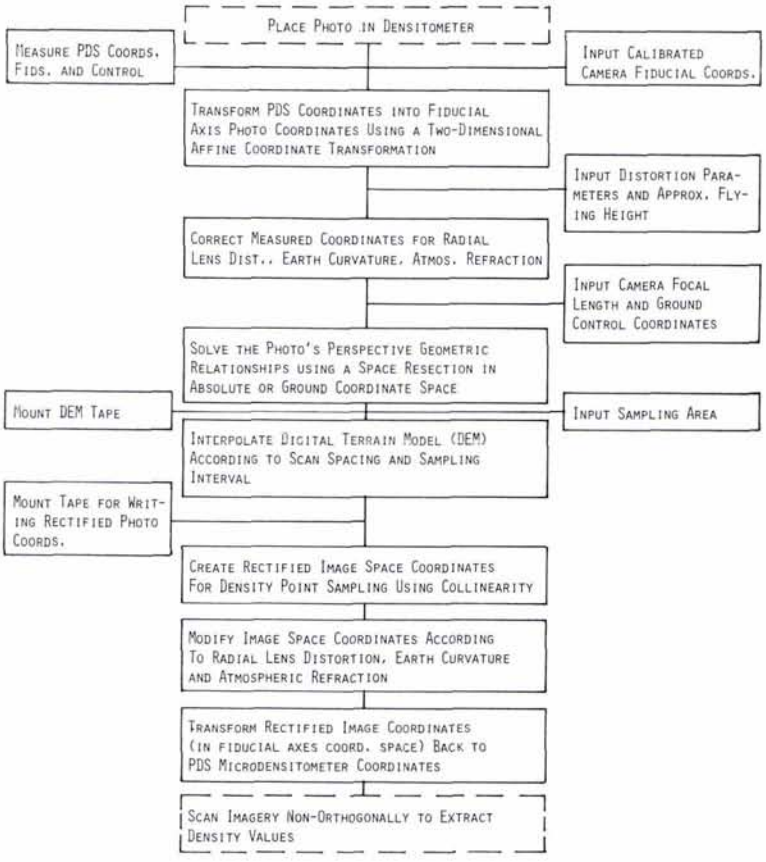

FIG. 1. Flow chart for software interface used to create orthophotography on a Perkin-Elmer PDS microdensitometer.

formation from transparencies or prints. The servo-driven x-y stage can scan 25 cm in each direction at speeds up to 400 mm per second with a relative accuracy of 0.005 mm (5 micrometres). Sampling can occur up to 25,000 times per second using a photometer with a range from 0.0 D to 4.0 D (density units) and 0.0 percent to 100.0 percent transmittance. The sampling areas are square and variable from 5 to 100 micrometres. A viewing screen enables the operator to see the magnified image of the area being scanned. An analog to digital converter digitizes the photometric information which is then stored along with positional coordinates on computer compatible magnetic tapes.

DIGITAL ELEVATION MODEL

The United States Geological Survey (USGS) provided a DEM on a 9-track 1600 bits/inch FORTRAN readable computer tape. This tape contains a typical 7½ minute quadrangle in the McCall, Idaho area. Included are the camera orientation and calibration parameters, the adjusted ground coordinates list, and film diapositives.

PROGRAM

OVERALL CONCEPT

The FORTRAN program was designed with two fundamental goals in mind: modular construction and flexible, interactive input-output. It was envisioned that the user might wish to bypass certain corrections or to expand upon the range of interpolation schemes available. The corrections to be applied as well as the output generated are controlled by a menu of ones or zeroes in the appropriate fields, indicating action (1) or inaction (0) in the processing of the data. Additional flexibility is assured by incorporation of the ability to read point names in any format, any order, and with multiple readings of any point.

PROGRAM STRUCTURE

The overall structure may be summarized: (1) read the menu, (2) input the ground control coordinates, (3) read the densitometer coordinates of the control and fiducials, (4) apply corrections, (5) compute the orientation of the photo by space resection, (6) read DEM data, (7) interpolate for desired spacing of points, (8) compute photo location of ground point by collinearity equations, (9) apply corrections, (10) output photo location to densitometer, and (11) repeat steps 6-10. This procedure may be generalized into a two-step approach: (1) compute the absolute orientation of the single photo by use of the collinearity condition equations, and (2) compute the position of that point on the photo using the camera orientation and ground coordinates of any point.

Execution begins by calling the various subroutines from the main program as requested through the data menu. Four corrections are available in addition to seven output choices. Each photo point may be modified by any combination of the following corrections: comparator calibration, radial lens distortion, atmospheric refraction, and Earth curvature. Output options which may be either viewed or suppressed are: echo the menu, print ground control, print densitometer coordinates, display affine transformation, print distortion corrections, print absolute orientation, and display final adjusted photo positions of the DEM points. The correction routines and associated equations are considered in more detail in the paragraphs which follow.

CORRECTION ROUTINES

Comparator Calibration Correction. Since the densitometer is used as a monocomparator for reading the plate coordinates of the control points, it is proper to consider the systematic distortions which result from differential scale changes in x and y as well as from non-orthogonality of the comparator axes. The procedure described by Jeypalan (1972) does not require a precisely etched grid plate because the least-squares solution carries both the comparator readings and grid values as unknowns. The mathematical model is:

$$x_c = S_1x' + S_2y' (\sin E)$$
$$y_c = S_2y' (\cos E)$$

where x', y' = comparator readings,
x_c, y_c = adjusted values,
S_1, S_2 = scale factors, and
E = angle of non-orthogonality

In practice the least-squares solution which solves for S_1, S_2, and E is a separate program since it need only be accessed periodically to recompute the calibration coefficients.

Affine Transformation. An affine transformation accommodates differential film shrinkage/expansion in the x and y directions while simultaneously rotating and translating from one coordinate system to another (Wolf, 1974).

Since the ultimate goal is to compute densitometer system coordinates for each point in the DEM, two separate affine transformations are implemented. The first transformation is from the densitometer coordinate system into the fiducial axis system; all subsequent coordinate manipulations take place in the fiducial axis system. When the photogrammetric computations are completed, the fiducial axis coordinates are retransformed into the densitometer system so that the densitometer scanner can be driven to that location. This procedure is required in all cases and is not considered an optional correction.

Radial Lens Distortion Correction. If a camera calibration report is available, the radial distortion characteristics of the lens will be known. Using this information, the radial lens distortion is approximated by the odd-power polynomial of the familiar form:

$$\Delta r = K_1r + K_2r^3 + K_3r^5 + K_4r^7$$

where Δr = distortion,
r = radial distance from the principal point, and
K = coefficients defining the shape of the curve.

Since the computation of the coefficients is needed only once for each camera, a separate least-squares program is used to compute these coefficients.

Asymmetric and tangential distortions are generally quite small and were not considered as contributing significantly to the error model. The assumption of symmetry was deemed reasonable for the purpose at hand.

Earth Curvature and Atmospheric Refraction Correction. The program utilized the following equation (Wolf, 1974) to compute the Earth curvature correction.

$$dr = \frac{H'r^3}{2Rf^2}$$

where dr = correction,
H' = flying height above ground,
r = radial distance from nadir,
R = Earth's curvature, and
f = camera focal length.

Schut's method of adjustment for atmospheric refraction (Schut, 1969) is employed when deemed necessary.

ANALYTICAL ABSOLUTE ORIENTATION

Having adjusted the raw plate coordinate readings by the previously selected algorithms, the next step is to compute the absolute orientation of the single photo by analytical resection.

At least three ground control points for which the X, Y, Z coordinates are available must appear in the photograph. Three such points will produce six equations which are sufficient for a minimum determination of the six unknown orientation parameters. Additional control points are used, however, to strengthen the solution. If the orientation of the photograph is already known, the program bypasses this section.

INTERPOLATION

In all likelihood, the selected sampling increment of the microdensitometer will not correspond to the availability of ground points; thus, the Z value of the desired point must be interpolated from the surrounding data.

A study by Leberl (1975) comparing the relative accuracy and computing time of six interpolation schemes revealed that a bilinear polynomial would adequately serve the needs of the microdensitometer program. The general form of the polynomial is:

$$Z = a_0 + a_1X + a_2Y + a_3XY$$

Should the user desire to try other polynomials, provision has been made to compute coefficients for any polynomial whose terms are specified in the data menu. The solution of either polynomial is by standard least squares using a slight variation introduced by Jancaitis and Junkins (1973). This variation optimizes the gridded nature of the sample data so that the least squares inverse need be computed only once. The usual least squares solution is of the form $\mathbf{X} = (\mathbf{A}^T\mathbf{PA})^{-1}\mathbf{A}^T\mathbf{PL}$. The variation allows the portion $(\mathbf{A}^T\mathbf{PA})^{-1}\mathbf{A}^T\mathbf{P}$ to be determined once with only the $\mathbf{L}$ vector changing for each new interpolation.

IMAGE COORDINATE COMPUTATION

After interpolating for the unknown elevation, Z, the collinearity equations are reentered with the previously determined camera orientation parameters and with the X, Y, Z coordinates of the ground point. The x, y image coordinates are then computed. The image coordinates may be "refined" by reintroducing radial lens distortion, refraction, and Earth curvature if desired by the user. This coordinate "refinement" should be viewed in the negative sense since the analytical solution considers only "pure" undistorted values while the actual image location of a point possesses whatever systematic errors were present in exposing the negative; it is this distorted image position that is sought by the densitometer.

Since the image coordinates are still referenced to the fiducial axis system, an inverse affine transformation is necessary to again relate the derived coordinates to the microdensitometer reference axis system. The computation involves simple substitution of the x, y values into the collinearity equations. Similarly, the inverse of the comparator calibration coefficients must be applied to the image coordinates so that the final x, y values will be those sensed by the densitometer circuitry. Only at this stage are the computed/manipulated coordinate values ready to be stored on tape.

OUTPUT

The program stores on tape the image density value for each interpolated elevation at a spacing consistent with the playback aperture size selected to create the orthophoto. Each string of densities represents the orthogonally correct position of that scene (density) in the ground coordinate system.

This tape, when rewritten onto light-sensitive film, creates the orthophoto. Any additional processing of the imagery can easily be introduced at this point.

ADVANTAGES

It was previously mentioned that an extremely high spatial resolution can be obtained because orthogonal playback of the original image density values is possible. Several other advantages become apparent as well.

Patch sizes are no longer restricted (economically or otherwise) to the millimetre range in size but are variable from 5 micrometres up to (typically) 100 micrometres or larger. The extremely fine resolution available, however, must be balanced with the exponential increase in computer time caused by additional interpolation of the DEM. Patch sizes as large as 200 micrometres produce imagery with no apparent disjoints to the naked eye even after a several times enlargement.

The system as envisioned can operate using a small computer and data storage facility since each operation is sequential rather than simultaneous with surrounding points. Non-orthogonal scanning can operate with one pixel at a time; a ground point is interpolated, the corresponding image location computed, and a density is extracted, digitized, and written onto tape. With each pixel stored in proper serial sequence, the normal playback of these strings of densities will reconstruct an orthogonal image. (The PDS Microdensitometer can be interfaced with a Digital Equipment Corporation PDP 11/34 having 32K of 16-bit words to manage the software package.)

As in the creation of orthophotography by conventional techniques, either image of the stereopair used to create the DEM can be used to create the orthophoto. Additionally, any image which can be related to the ground space (through collinearity or other appropriate rectifications) can be reconstructed in true orthophotographic position (Konecny, 1976). The program as developed can handle single oblique photographs of DEM's whenever three or more control points can be determined within the photograph's area.

Annotated information and contour lines are introduced during playback of rectified imagery by modifying the individual density pixels. White contour lines can be simulated, for example, by replacing the actual density value of pixels at selected elevations with density values of zero. Upon reconstruction of the imagery, the connection of these modified pixels will create the contour lines. Additional data processing is required so that smoothed, continuous, labeled contours could be generated.

RELATED APPLICATIONS

Digital elevation models are only one form of the terrain information which could be used to rectify imagery. Existing contour maps also could be used to create the DEM which, in turn, would rectify imagery depicting the area.

A very simple modification to existing analytical stereoplotters would allow them to extract image densities for the purpose of creating orthophotos. Typically, each film carrier is encoded and motorized and each photogrammetric operation can be related (through system-oriented software) to an x and y coordinate location on either of these film carriers. Either carrier can be transformed into a microdensitometer by inserting a calibrated light source and a photometer into the optical train. The light source and collector would be designed to operate in the non-visible portion of the electromagnetic spectrum so as not to interfere with the normal light source used to view the imagery. An analog-to-digital converter would also be needed.

As ground elevation points are determined, the densities of corresponding image points can be extracted directly. A dynamic aperture system would be used so that points at different elevations (at different scales) would be sampled with the appropriately-sized aperture. These rectified density points would then be rewritten to create the orthophoto. A light-tight cassette would then replace the film diapositive to facilitate this computer-driven playback. The tape also could be processed commercially by a microdensitometer firm to produce the orthophoto.

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