REAL TIME PROCESSING OF MOMS-02 LINEAR ARRAY IMAGERY FOR ANALYTICAL STEREO RESTITUTION

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Abstract
Analytical stereo restitution of analog hardcopy transparencies produced from two image channels of the MOMS-02 Three-Line-Camera may be considered as suitable substitute for a pure digital restitution yet to come. The paper describes a novel approach for the corresponding real-time process on ordinary analytical stereoplotters. Continuous provision of the exterior orientation data - assumed to be given - for each line of the two linear array images (forward/nadir; forward/backward; nadir/backward) is one of the essential features. The rigorous solution, based on an iterative algorithm, requires substantially more computing power than is needed for conventional perspective frame imagery. Running on a VAXstation 3100/38 host computer, the algorithm has been tested with analytically simulated satellite imagery and has shown the principal feasibility of this approach. Further tests with airborne MEOSS imagery will follow. It is intended to implement the algorithm in the PHOCUS environment of the Zeiss Planicomp P-Series.

1 Introduction

Photogrammetric stereo restitution of analog photographs is a fundamental process for model reconstruction of 3D-objects. It is predominantly utilized on stereo compilation instruments, e.g. analytical stereo plotters, for the production of topographic maps, geo-information systems and digital terrain models in various scales. The human stereo operator not only measures 3D-positions but also has to perform a certain amount of image interpretation. It is this interpretativity that cannot be modelled completely by computer vision methods as yet, thus making human interference in 3D-measurements of pictorial data essential for a long time to come. This statement is valid even when purely digital stereo workstations [Siebe, et. al., 91] are considered.

In view of the fact that analytical stereoplotters encompass mature hardware and software features with which enormous experience in restituting metric frame photography has been gained, it is worthwhile to investigate the possibility of restituting analog MOMS-02 imagery derived from its originally digital data. Based on the push broom principle of linear array scanners, MOMS-geometry [Ackermann, et. al., 91] differs considerably from the perspective geometry of frame photography Fig.1.

In an older paper [Konecny, et. al., 87] have shown the principal feasibility of restituting analog SPOT-imagery on analytical stereoplotters. Contrary to that approximative solution utilizing a fictious 3D-correction grid in the vicinity of the stereo model, here a novel rigorous approach will be described. Although derived and tested on the basis of the MOMS-configuration, it nevertheless may be applied to other linear array imagery as well. In addition, the procedure can easily be transformed from analytical to digital restitution.

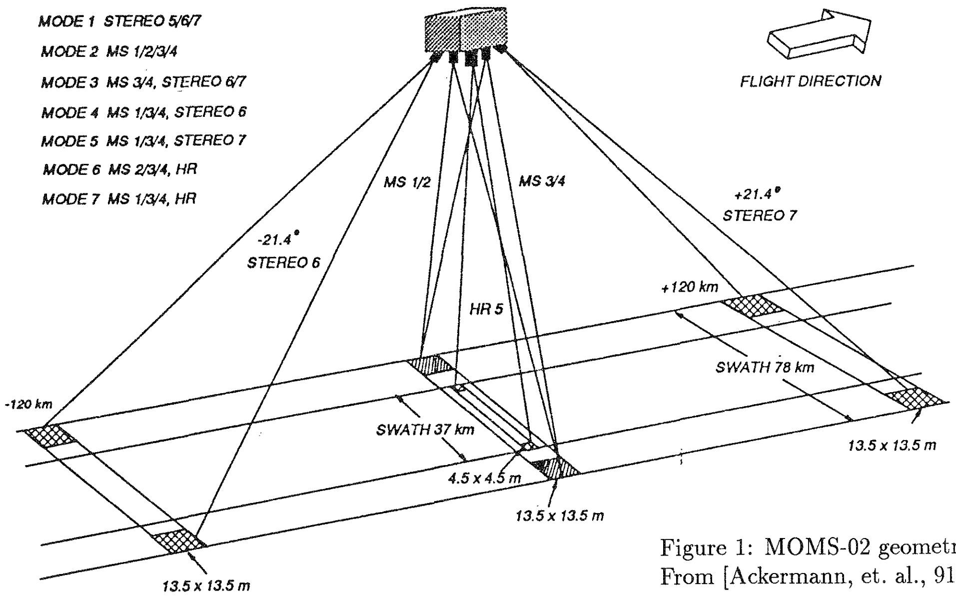

Figure 1: MOMS-02 geometry
From [Ackermann, et. al., 91]

2 Mathematics of the imaging process

Image generation with linear CCD arrays is a kinematic process, because the lines are recorded continuously to cover the object without any gaps. The sensing frequency is determined by the velocity-to-height ratio of the moving platform and the pixel size-to-focal length (principal distance) ratio of the sensor. Each recorded line belongs to a discrete recording time with its own orientation of the sensor camera [Hofmann, et. al., 84].

The camera (sensor) coordinate system ($\mathbf{x}$) or $\overset{C}{\mathbf{X}}$ is defined for each sensor array separately, otherwise analogously to ordinary frame cameras, whereby its origin is set to the middle of the first pixel of the sensor array $\overset{C}{X}_{IO}$. In addition, the construction parameters of the sensor array line have to be known, e.g. the number of pixels per line, the size of the pixels (width and length). The y-axis is assumed to coincide with the length axis of the sensor array, the x-axis perpendicular to it and in the plane of the array. All pixels have zero x- and only positive y-coordinates. Catenation of successive array lines accumulating after projection on an image plane assumed to be parallel to the momentaneous direction of flight, defines the photo coordinate system $\overset{P}{\mathbf{X}}$, starting with a suitably chosen line number offset, and the pixel number. The line number is a linear function of the recording time. While for the triangulation process three linear arrays are essential to solve the path and attitude (i.e. exterior orientation) of the sensor camera [Ebner, et. al., 91], for stereo restitution only the images of two arrays can be utilized simultaneously.

The fundamental equations are identical to the collinearity equations for perspective frame imagery, with the noticeable exception that the exterior orientation parameters are functions of time for a continuous approach, or of the line number for the discrete case. The following general derivation is based on the continuous domain, later specializing on the discrete.

Specifying exterior orientation by the (3,4)-matrix $\mathbf{O}(t) = [\mathbf{C}(t), \mathbf{R}(t)]$ where $\mathbf{C}$ represents the world coordinates of the perspective center and $\mathbf{R}$ the rotation matrix of the camera system within the world system, then the normalized camera coordinates ξ of a world point $\mathbf{X}$ are given by.

$$\xi(t) = \frac{(\mathbf{X} - \mathbf{C}(t)) \cdot \mathbf{R}_{,12}(t)}{(\mathbf{X} - \mathbf{C}(t)) \cdot \mathbf{R}_{,3}(t)} \tag{1}$$

$$= \mathrm{persp}(\mathbf{O}(t), \mathbf{X}) \tag{2}$$

In this equation the time parameter is determined by the condition that for the particular world point the abscissa value ξ_1 must vanish:

$$\xi_1(t) = 0. \tag{3}$$

Analytically this is equivalent to solving the nonlinear equation (1) subject to the constraint (3). This leads to an iterative process since Equ.(1) can only be solved for t through linearization. From

$$\xi(t + dt) = \xi(t) + \dot{\xi}(t)dt \tag{4}$$

and employing condition equation (3) we obtain

$$dt = -\frac{\xi_1(t)}{\dot{\xi}_1(t)} \tag{5}$$

where

$$\dot{\xi} = -\frac{\partial \mathrm{persp}}{\partial \mathbf{O}} \cdot \dot{\mathbf{O}} \tag{6}$$

are the derivatives of the normalized camera coordinates with respect to time.

As the shuttle is assumed to move more or less parallel to the world coordinate system, Equ.(6) may be substantially reduced to the approximative form

$$\dot{\xi}_1 = -\frac{\dot{C}_1}{X_3 - C_3} \tag{7}$$

For real image coordinates $\mathbf{x}$ Equ.(7) modifies to

$$\dot{x}_1 = \frac{c_3 \cdot \cos(\theta)}{X_3 - C_3} \cdot \dot{C}_1 \tag{8}$$

where c_3 represents the focal length of the sensor camera and θ the angle between pixel plane, i.e. camera image plane, and accumulating photo image plane.

In the sequel another notation will be used for the actual discrete case. In tensor notation, Equ.(1) may then be written for real coordinates as

$$\overset{C}{X}_{P\alpha} = \overset{C}{X}_{IO\alpha} - \overset{C}{X}_{IO3} \cdot \frac{(\overset{W}{X}_{P\mu} - \overset{W}{X}_{PC\mu}(i))r_{\mu\alpha}(i)}{(\overset{W}{X}_{P\mu} - \overset{W}{X}_{PC\mu}(i))r_{\mu 3}(i)} \tag{9}$$

$$\alpha = 1..2$$

$$\mu = 1..3$$

$\overset{C}{\mathbf{X}}_{IO}$	Interior Orientation, Camera (space) coordinates of the perspective center (PC)
$\overset{C}{\mathbf{X}}_{P}$	Camera coordinates of Point P, inside the interval of sensor width and length
$\overset{W}{\mathbf{X}}_{P}$	World (model) coordinates of Point P
$\overset{W}{\mathbf{X}}_{PC}(i)$	World (model) coordinates of the Perspective Center (PC) according to i
$r_{\mu\nu}(i)$	Rotation matrix $\mu = 1..3, \nu = 1..3$ from system W to C according to i $\overset{W}{\mathbf{R}}_{C}(i) = \mathrm{rotmat}(\omega(i), \varphi(i), \kappa(i))$

3 Real-time algorithm

The purpose of the real-time programm for an analytical stereoplotter is to continuously provide a connection between world (model) coordinates of an arbitrary world (model) point - represented by the operator controls - and its two corresponding photo/image points - represented by the floating mark associated with the two photos/images.

The transformation of world (model) coordinates to camera coordinates is governed by the collinearity equations (9) applied to each linear array image individually.

For simplicity reasons the real-time algorithm is discussed for one linear array image only, starting with some state of stationarity. In such a case the object point, given by its world coordinates $\overset{W}{\mathbf{X}}_P$, the perspective center $\overset{W}{\mathbf{X}}_{PC}(i)$, connected to the camera rotation $\overset{W}{\mathbf{R}}_C(i)$ by the proper line number i, and the corresponding image point, given by its camera coordinates $\overset{C}{\mathbf{X}}_P$, are on a straigt line, intersecting the sensor array. In this stationary situation the quantities in Equ.(9), including the orientation parameters $\overset{W}{\mathbf{X}}_{PC}(i)$, $\overset{W}{\mathbf{R}}_C(i)$, match each other via the corresponding line number i. Changing the values of the world coordinates $\overset{W}{\mathbf{X}}_P$, i.e. by means of the operator controls, disturbs the stationarity, and the purpose of the real-time loop is to regain the correct connection for the quantities in the Equ.(9) via the line number i.

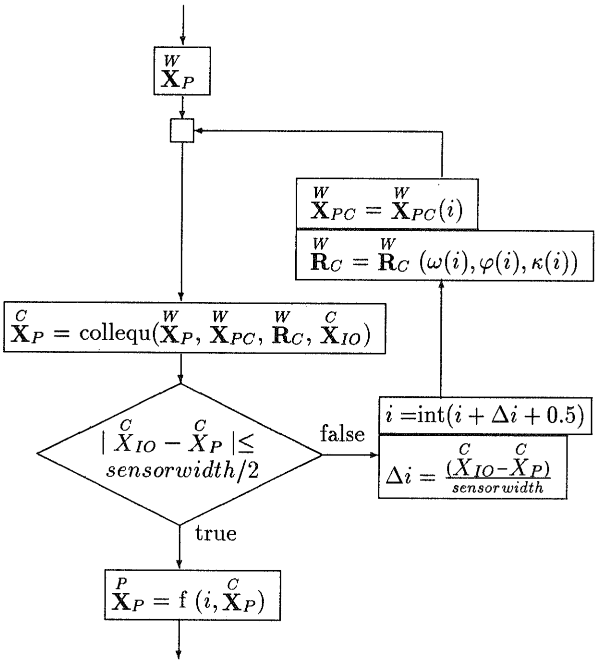

Figure 2: Real-time algorithm

The flow diagram in Fig.2 may serve for an explanantion of the algorithm for one particular sensor array. The perturbed world coordinates $\overset{W}{\mathbf{X}}_P$ together with the orientation parameters corresponding to the previous line number i, determine new camera coordinates $\overset{C}{\mathbf{X}}_P$ via the collinearity equations (9). Normally, the corresponding image point will not fall on the permissible array area. The abscissa difference of $\Delta \overset{C}{X}_P = \overset{C}{X}_{IO} - \overset{C}{X}_P$ is a measure for the (linear) movement of the camera platform necessary for imaging the new point $\overset{W}{\mathbf{X}}_P$ onto the sensor array. The $\Delta \overset{C}{\mathbf{X}}_P$ corresponds to a certain line number increment Δi. If $| \Delta i | > 0.5$, then the computations have to be repeated with the orientation parameters belonging to the new $i = \text{int}(i + \Delta i + 0.5)$ line number. Otherwise the correct line number pertaining to the correct point has been found, and stationarity regained. Now the camera coordinates can be transformed to photo coordinates.

$$\begin{aligned} \overset{P}{X} &= \overset{C}{X} + pixelwidth \cdot i + offset \qquad (10) \\ \overset{P}{Y} &= \overset{C}{Y} \end{aligned}$$

4 Analytical plotter implementation

The estimation of transformation parameters between photo coordinates and stage coordinates is part of a process analog to interior orientation of frame pictures; as fiducial points the four image corners are used. The transformation from photo into stage coordinates itself is part of the real-time program, making it possible to account for other corrections as well.

The analytical stereo plotter Planicomp P-series of Carl ZEISS, Oberkochen has a dedicated processor, denoted P-processor. The task of this processor is to keep the connection between world (model) coordinates, introduced by the operator controls, and the photo coordinates of the corresponding image point in both photographs and move the carriers to the calculated position. Having been designed for the restitution of metric photographs with perspective geometry only, i.e. the collinearity equations are calculated with one particular perspective center for each photograph, the processor in addition supplies an opportunity to continuously accept additional stage (or photo, or model) coordinate correction values from a host computer via data transfer.

These features lead to a loop construction as shown in Fig.3 for one image. The P-processor evaluates the collinearity equations with an approximate orientation obtained from the middle of the entire camera path of the particular image, transformed to a near nadir image (see also Equ.(8)). The host program goes through the algorithm shown in Figure 2 added by the transformation from photo to stage coordinates. In order to avoid additional communication between P-processor and host, the P-processor computations are copied by the host. The differences between either stage coordinates for scanner geometry and perspective geometry are transmitted as corrections to the P-processor.

The rigorous solution not only is general, it is also flexible enough to be utilized as module for other linear array scanner imagery. Although true for SPOT stereo imagery in principle, slight modifications would be required due to a stereo configuration orthogonal to MOMS-02. For other imaging geometries, the module may easily be replaced. As of today, only an experimental version is available.

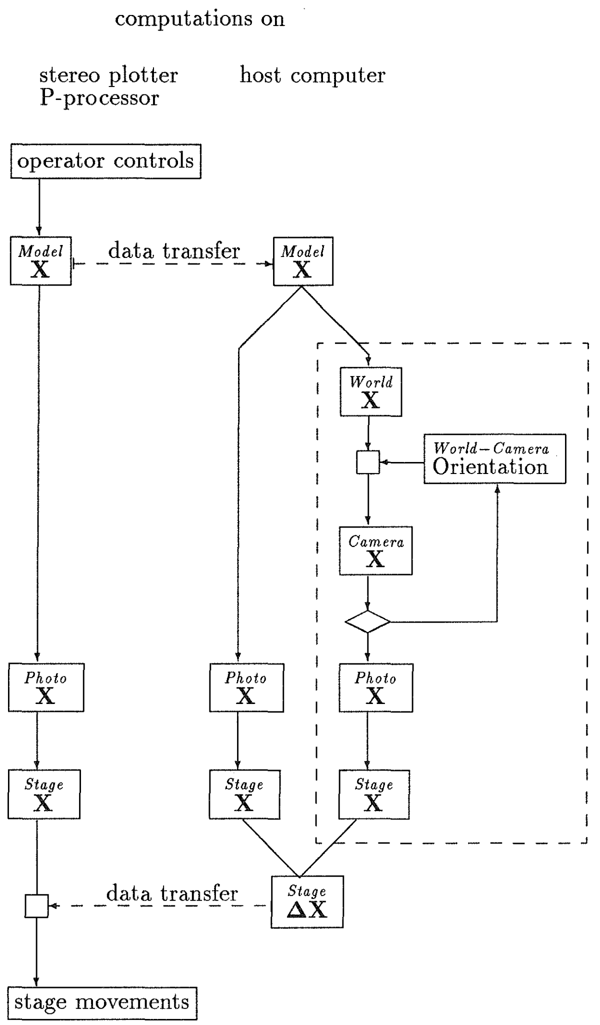

Figure 3: overview and interaction

5 Simulation and operational aspects

The three linear arrays of MOMS-02 allow for different modes of stereo restitution. The normal mode makes use of the forward and backward looking channels. Both have identical resolution (forward and backward: 13.5×13.5m on the ground), and the convergence angle of 2×21.9° is the geometric prerequisite for a reasonable elevation accuracy. The combinations of forward and nadir or nadir and backward looking channels have different resolutions for the left or right image (nadir: 4.5×4.5m on the ground). For optimal stereo perception both images have to be brought to the same scale. The final image scale is determined by the type of device used for the transformation of the digital data to analog film. The smaller convergence angle of 21.9° will be compensated for - at least to some degree - by the higher resolution of the nadir looking channel.

The digital-to-analog image data conversion will be performed on the FIRE image printer of DLR (German Aerospace Establishment), Oberpfaffenhofen. The FIRE is capable of producing images on analog film up to 8800×9600 pixels with a minimum size of 25μm. This is equivalent to a maximum picture size of 220×240mm which almost exactly corresponds to the size of the picture carriers (230×230mm) of the Planicomp.

For the forward/backward MOMS stereo channels (6000 pixels of 10μm each; ground resolution 13.5m) the effective lateral picture width will be 150mm, corresponding to a swath width of 79km. In order to fully exploit the picture carrier format in the direction of the camera movement, more than 9000 array lines may be utilized, corresponding to 120km. Individual stereo scenes on the Planicomp may therefore cover an area of 120×79km^2.

If one of the two pictures is derived from the nadir channel (8400 pixels; ground resolution 4.5m) the necessity of equal photo scale for both pictures requires that the nadir resolution be reduced by a factor three (13.5m by 4.5m) yielding an effective lateral picture width of 70mm only. This reduces the area of the stereo scene to 120×37km^2.

By fully exploiting the resolution of the nadir channel, its 8400 pixels will give a picture width of 210mm at the maximum FIRE resolution (25μm). This requires a FIRE resolution of 75μm for the two other stereo channels, i.e. only some 3000 pixels may be effectively utilized. For the length of the picture in flight direction some 9000 nadir channel lines and some 3000 forward/backward channel lines are needed. Individual stereo scenes will cover an area of 37×40km^2. While this version corresponds to a picture scale of 1:180 000, the other version entails a scale of 1:530 000.

In order to gain smooth movements of the stereo plotter photo carriages two features are important. Firstly, the changes in the correction values should be small when the world coordinates are changing, secondly the computations should reach real-time speed. Concerning the main problem of this approach, viz. the real-time aspect, a frequency of some 50Hz is considered to be standard in analytical stereo plotters to allow for continuous visual stereo perception. The processing time of the compound loop is influenced mainly by the computing power but also by the amount of calculations and the convergence rate of the iteration (stability is reached with $\approx$ 3 iterations) and by the communication tasks (minimized) between P-processor and host.

The testing equipment consists of a standalone VAXstation 3100/38-24MB connected to a Planicomp P2 via IEEE 488 (GPIB) interface, and the software prototype runs as single process with the data of exterior orientation points [Ebner, et. al., 91] stored in main memory and linear interpolation. Up to now, experience has shown that operational restitution is possible with smooth image movements and corrections supplied in real-time. With simulated test data based on the MOMS-configuration stereoscopic height measurements have shown a repeatability precision of 4-5m and an accuracy of some 10m when compared to exact reference values.

Further tasks will be the integration of the prototype program into the PHOCUS environment. This will lead to a loss of computing performance because there are concurrent processes needing computing, communication and synchronising capacity. Some refinement of the functional approach (e.g. earth curvature correction, interpolation of orientation parameters, optimizing iteration convergence) are presently under development. Further tests with airborne MEOSS linear array imagery are intended.

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