CORRELATION TECHNIQUES AND DEVICES

I n v i t e d   P a p e r

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by

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Abstract

First a review of image correlation techniques is given according to the photogrammetric and mathematical fundamentals as well as the techniques for video-conversion, correlation and rectification of videosignals.
Then the paper traces the historical development of automatic image correlation devices from the Hobrough Stereomat, via the Bunker Ramo Unamace to the Hobrough Gestalt System and the Bendix AS-11-BX.
Reference is made to the Rastar Correlator under development at the University of Hannover, based on designs by G.Hobrough and completed by D.Pape.
Finally other experimental attempts for image correlation, such as (coherent) optical correlation and digital off-line correlation are summarized.

1. Introduction

Image correlation is a procedure to compare an image, consisting of a two-dimensional sequence of grey-level variations, with a reference image of similar, but not necessarily identical grey-level variations, in order to detect differences in geometry between these two images. The differences can then be utilized in order to bring the image into register with the reference image or in order to derive other control signals from them.

In photogrammetry image correlation techniques have been invented and utilized with the main purpose to derive height information from stereoscopic images in form of x-parallaxes. This was particularly desirable since the measurement of heights by the operator constitutes a considerable human effort, which can then be replaced by an automatic device operating faster with a nearly equivalent performance. Correlators have also been used to measure y-parallaxes for the purposes of relative orientation. Correlators can also be adapted to the automatic measurement of symmetrical signals for which the reference image consists of a given symmetrical signal pattern.

In photogrammetric image correlation the impetus has mainly come for the field of electronic signal processing. The photogrammetrist's interest and influence has mainly been to define the control functions in the photogrammetric evaluation process. The means of achieving the correlation task has been left to the designer of electronic components. He in turn has had reasons or difficulties in communicating his design experiences to the photogrammetrist. The photogrammetrist in turn has decreased his interest as soon as it became evident that electronic image correlation has inherent difficulties: For example heights are measured for areas instead of points or undesirable information from buildings or trees cannot be eliminated. The photogrammetrist's interest was even more diminished after it became clear that image correlation despite of it relative speed increase of one magnitude meant a cost increase of not one but two magnitudes for the hardware.
Advantages for automatic correlation could therefore only be demonstrated for very large organizations, having a nearly infinite demand for photogrammetric evaluation products. For these the use of correlators means an increase of their production.

The recent electronic design trend toward less expensive design components gives rise to new hopes, that electronic image correlation may become economically competitive with fully operator-controlled stereo-evaluation also for the typical photogrammetric plant, having a limited product demand.
This process must be viewed under the following aspects: Electronic correlators have with few exceptions up to now been designed as total systems. This has made them largely incomprehensible, vulnerable, unserviceable and most certainly very expensive. Nowadays analytical plotter development has been generally accepted in photogrammetric instrument design. An analytical plotter possesses a large part of the components of a photogrammetric image correlation system. It is therefore sufficient to build a correlation device as an added processor to an analytical plotter

to have it function as an on-line automatic image correlation system.
Other avenues have been opened by the increased speed capacity and flexibility as well as by the decreased cost of computers in general.
Off-line correlation of digizized image information has become a feasibility.
Off-line correlation has the advantage of requiring a minimum of special hardware. On-line correlators, however, have the benefit of refined performance with respect to the quality of measurement and the avoidability of losses because more easily hierarchical decision strategies may be introduced in real time. They also do not have to cope with the large problem of off-line correlation in having to store and address immense quantities of digital data, if a sufficient performance is to be reached.

In this time of changed prerequisites it is quite proper to analyze the past and present achievements in image correlation techniques, but it is even more important to ask the photogrammetric manufacturer and the photogrammetrist in general to become now fully aware of the potential of image correlation in the future.

2. Correlation Techniques for Electronic Correlation

2.1. Photogrammetric Fundamentals

The general task of correlating two images for geometrical differences can be largely simplified, if some information about the geometry is known.
In this way the known transformation parameters may be applied to both images, and the correlation task becomes restricted to those parameters which are not predeterminable.

In aerial photography an image point x'y' is related to a ground point x,y,z by the collinearity equations:

$$x' = x'_c - c\,\frac{a_{11}(x-x_o)+a_{12}(y-y_o)+a_{13}(z-z_o)}{a_{31}(x-x_o)+a_{32}(y-y_o)+a_{33}(z-z_o)} + \Delta x'$$

(1)

$$y' = y'_c - c\,\frac{a_{21}(x-x_o)+a_{22}(y-y_o)+a_{23}(z-z_o)}{a_{31}(x-x_o)+a_{32}(y-y_o)+a_{33}(z-z_o)} + \Delta y'$$

They contain:

1) the 3 known parameters of interior orientation x'_c, y'_c and c

2) the exterior orientation parameters: of these x_O, y_O, z_O are the 3 exposure station coordinates in the ground system. The 9 coefficients a_{11} to a_{33} are functions of the 3 camera rotations ω, ϕ, κ with respect to the ground coordinate system, defined by a rotational matrix.
Relative orientation of one image with respect to the other, in which the image is reprojected to the reference image to

coincide in 5 different points permitting only z-variations, determines 5 of the exterior orientation parameters

3) the image displacements $\Delta x'$, $\Delta y'$ caused by distortions of various kinds such as:

   a) lens distortion as function of x'y'
   b) film deformation as function of x'y'
   c) refraction as function of exterior orientation
   d) coordinate system deformation (deviations from orthogonality of the ground coordinate system)

Photogrammetric restitution instruments are capable to compensate with plotting accuracy for most, if not all, of these deformations:

Photogrammetric cameras operate nearly lens-distortion free and the deformations of film, refraction and the ground coordinate system are generally negligible in plotting. Analog plotters use optical or mechanical projection of the images by making use of the known or otherwise determined or assumed 3 interior and 6 exterior orientation parameters of each photograph. Analytical plotters establish the relations by a digital solution of the collinearity equations.
But plotters only solve the relationship for one point. The point setting includes stereoscopic measurements by the operator involving a correlation process in his brain. Automatic image correlation techniques therefore require to be applied to a two-dimensional sequence of points: This is principally possible in the following ways:

1) The images are projected by the colinearity equations onto a rectified image plane which serves as a basis for correlation. The first Hobrough Stereomat operated on images projected onto the plateau of a Kelsh plotter in this manner. Also the IBM-DAMCS rectified the image before digital correlation. This "model space correlation" has the advantage of an optimal correlation geometry. It has the disadvantage, however, of grey level losses during the analog projection or of tedious resampling operations in digital projection.

2) It is possible to select other model spaces than the reprojection onto a rectified image plane:
   Such a possibility is the selection of a sequence of corresponding epipolar lines in the two images. An epipolar line is the trace (intersection) of the model plane defined by a ground point and the two exposure stations in the plane of the photograph. Calculation of the corresponding epipolar lines involves selection of a ground point, calculation of the two corresponding image points x'y' and x"y" by collinearity equations and the calculation of the directions of the epipolar lines dy'/dx' and dy"/dx" by explicit or implicit means. Epipolar correlation, first applied by Helava in the AS-11-BX reduces the problem to transform thousands of image points by projection. Instead it restricts itself to the projection and correlation of only hundreds of points along an epipolar line.
   This is possible by a moderate digital computation effort in real time.

3) "brute-force image correlation"

utilizes area sensors which may or may not have been positioned to corresponding points x'y' and x"y". Such correlation uses as input images, which have not yet been geometrically transformed.
The geometric transformations for correlation can be achieved during the correlation process in two ways:

a) either at first no transformation at all is applied and subsequent transformation parameters are calculated from a first rough correlation; the process is iteratively improved

b) or a sampling algorithm operating according to collinearity equations is applied in order to select a specific sequence of image points. Such a procedure can generally operate fast enough only when electronic circuity combined with flying spot scanner sampling is applied. Such a procedure may also be useful in off-line digital correlation.

Image correlation has as its aim to register images or transformed images. While the described displacements caused by parameters of interior and exterior orientation including the various distortion types affect image portions individual height displacements Δz are those which vary most in the model and which are detectable in the projected images as x-parallaxes, as parallaxes along the epipolar line in an epipolar system or as terrain samples obtained by the brute force correlator.

To detect these variations in Δz as a function of x, $x_{epipolar}$ or as some other function of x',y' a limited window must be defined in which correlation in 2 or at least in 1 dimension is performed in order to define z from a selected number of points characteristic for this limited sample (see Fig.1). It is possible to treat the sampled information referring to a region in such a way as to favour its mean or its center and even, to derive z as function of the sampled sequence. In this respect the width of the correlation window assumes an important role.

Image correlation is also influenced by photometric distortions resulting from different viewing angles, which cause different reflection characteristics affecting in general the low frequency component of the grey level sequences but also high frequency details (see Fig.2).

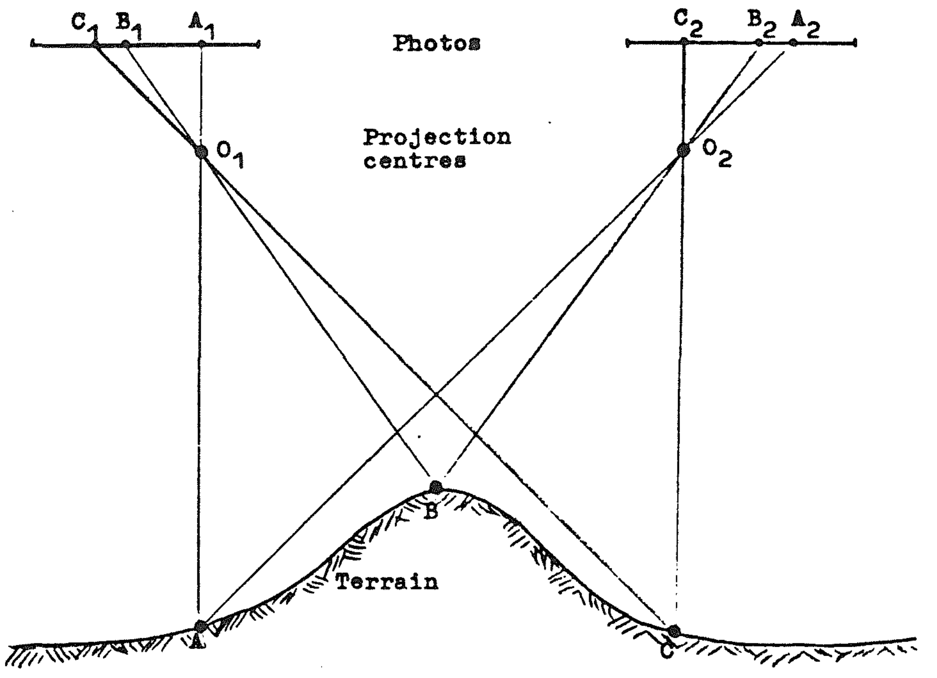

Fig.1: Geometric distortion by terrain elevations

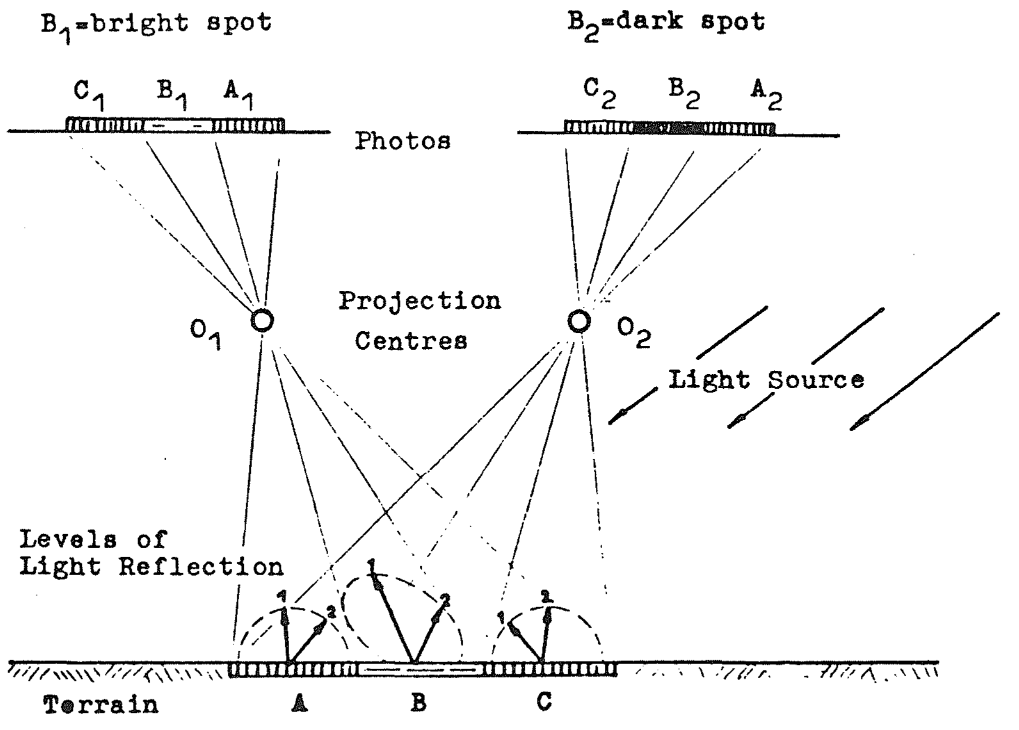

Fig.2: Photometric distortion by different reflection in different viewing angles.

2.2. Mathematical Fundamentals

For the determination of a best match for two corresponding one-dimensional signal sequences (original or transformed) a correlation algorithm must be used:
If A(t) is the sequence of grey level signals contained in the reference photo and B $(t+\tau)$ the sequence of grey level signals contained in the photo to be shifted, the shift being characterized by τ in the signal sequence, then the correlation integral $R(\tau)$ valid for the correlation window -T to +T is given by

$$R(\tau) = \frac{1}{2T} \int_{-T}^{T} A(t) \cdot B(t+\tau)\, dt; \qquad (2)$$

The correlation integral can be calculated for sequence of signals

$A(t)$ and $B(t+\tau)$

chosen arbitrarily.
Then one of the signals is shifted by Δ_i (and by negative and positive multiples thereof) and the $R(\tau+\Delta_i)$ are again calculated:

$$R(\tau+\Delta\tau_i) = \frac{1}{2T} \int_{-T}^{T} A(t) \cdot B(t+\tau+\Delta\tau_i)\, dt; \qquad (3)$$

One of the values calculated for $R(\tau+\Delta\tau_i)$ will become a maximum and this $\Delta\tau_i$ will be the required optimal shift. $\Delta\tau_i$ is directly proportional to the required change in Δz.

1) The correlation integral to be maximized may be replaced by other functions of identical or at least similar effect:

2) The correlation integral expressed as finite correlation coefficient:

$$r(\Delta\tau) = \frac{\Sigma\, A(t) \cdot B(t+\Delta\tau)}{\Sigma(A(t))^2 \cdot \Sigma(A(t+\Delta\tau)^2} \qquad (4)$$

this coefficient is to be maximized.

3) the covariance of the two signals, to be maximized

4) the square sum of the residuals, to be minimized

5) the absolute difference of the residuals, to be minimized

6) the cross correlation of the Fourier spectra of the two images, to be maximized

7) the correlation intensity I to be maximized:

$$I(\Delta\tau) = \sqrt{\Sigma|A(t)|^2 + \Sigma|B(t+\Delta\tau)|^2}; \qquad (5)$$

The optimal determination of $\Delta\tau$ in the two directions Δx (or $\Delta x'$)

and Δy (or $\Delta y'$) becomes a function of the grey level distribution and its disturbances. It is possible to optimize its determination by the proper choice of filtering operations.
It is desired to reduce the number of required computations then the difference of the chosen corrleation algorithm function can be selected as a measure to control the computation process:

$$\Delta R(\tau) = R_1(\tau) - R_2(\tau) \quad ; \qquad (6)$$

with

$$R_1(\tau) = \frac{1}{2T} \int_{-T}^{+T} A(t+\Delta\tau) \cdot B(t+\tau)dt; \qquad (7)$$

$$R_2(\tau) = \frac{1}{2T} \int_{-T}^{T} A(t) \cdot B(t+\tau+\Delta\tau)\, dt; \qquad (8)$$

Likewise other algorithms than the correlation integral are applidable. $\Delta R(\tau)$ permits to control and converge the image correlation process toward a state of maximization of the correlation integral (correlation coefficient) or the minimization of the parallax difference (square sum of residuals).
$\Delta R(\tau)$ to be minimized may also be obtained by differentiating the signal $R(\tau)$ to be maximized.

2.3. Video-Conversion

In the photographs the total image information is available simultaneously (in parallel). To make this information electronically accessible, it must be converted into a serial sequence of electric signals. For this purpose the photographs are quantized into smallest image elements and these are sequentially or in group transmitted to electrooptical sensors. Sensors to convert density differences of images into electric currents have been conventionally photo-cathodes or solid state sensors.
Photo cathodes embrace photo-cells, photo-multipliers and vidicons; solid state sensors resemble photo-diodes especially those combined into arrays. In order to permit a sequential scanning the image elements are either simultaneously imaged onto a group of sensor elements, which are serially interrogated element by element (vidicon, diode-arrays) or which are serially illuminated and imaged by a single photo sensor (flying spot CRT, laser, Nipkow-disk). In modifying and processing of the analog signals non-predicable disturbances may be generated by thermal noise and by foreign sources. In this respect the flying spot Laser and the photodiode array have proven to be very useful.
After digitization of the signals these error influences disappear almost completely, so that an early A/D conversion is considered desirable in the course of signal processing.

2.4. Correlation of Video Signals

Correlation of the two videosignals derived from both stereo images may be analog or digital. The digital procedure has its advantages.The functions to be performed are: Delay, multiplication, integration and subtraction. Furthermore filtering operations are most essential in order to diminish the sensibility to obtain side-maxima of the correlation integral. Fig.3 describes the realization of a correlator according to formula (3). Fig.4 describes the realization of a correlator according to formula (6).

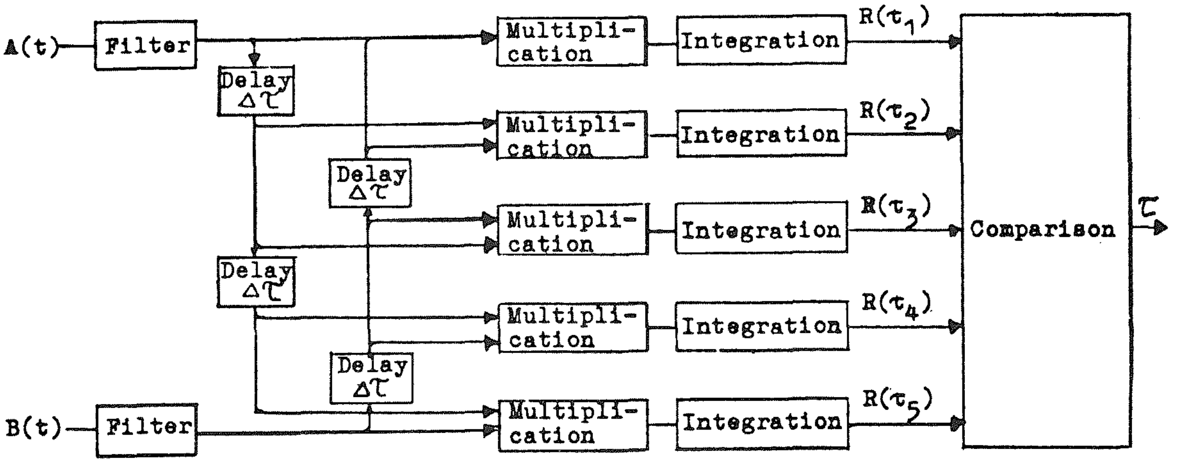

Fig.3: Establishing parallax from maximum correlation function

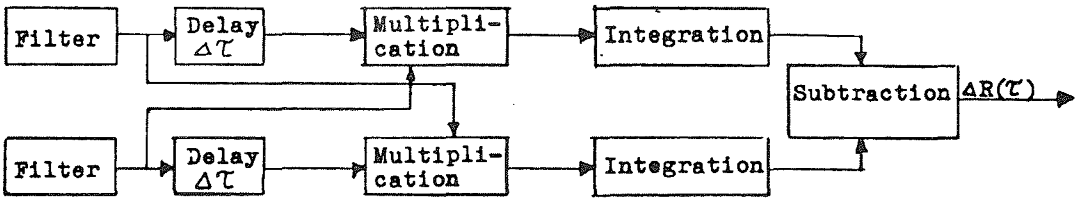

Fig.4: Establishing slope of correlation function for subsequent parallax elimination

By the choice of suitable frequency bands of the filters and by suitable choices for $\Delta\tau$ the parallax can be determined in several steps beginning with the large area image content going on to the finest image details.

2.5. Rectification of Videosignals

Even if there are no correction possibilities for the photometric differences of the two images to be correlated, the geometric distortions, particularly those due to elevation differences, may be determined and corrected well. For this purpose both photos are controlled in an independent manner:
One possibility for rectification exists as follows:
A number of image elements, sufficient to cover the range of the maximum expected parallax, is stored electronically. In this case rectification can occur later digitally. The advantage of this procedure is that rectification is independent of image scanning performed before. Therefore image scanning may be greatly simplified using a regular scanning mode. The control of rectification process occurs during correlation from parallax values obtained.

Another possibility for rectification exists in controlling the sampling in speed or direction of scan. In this case the hardware effort is considerably larger.
Fig.5 shows the principle of a correlator with electronic rectification. With appropriate scaling the rectification may correspond to information contained in an orthophoto. The output may not only be in form of parallaxes, but also directly as Δz-values.

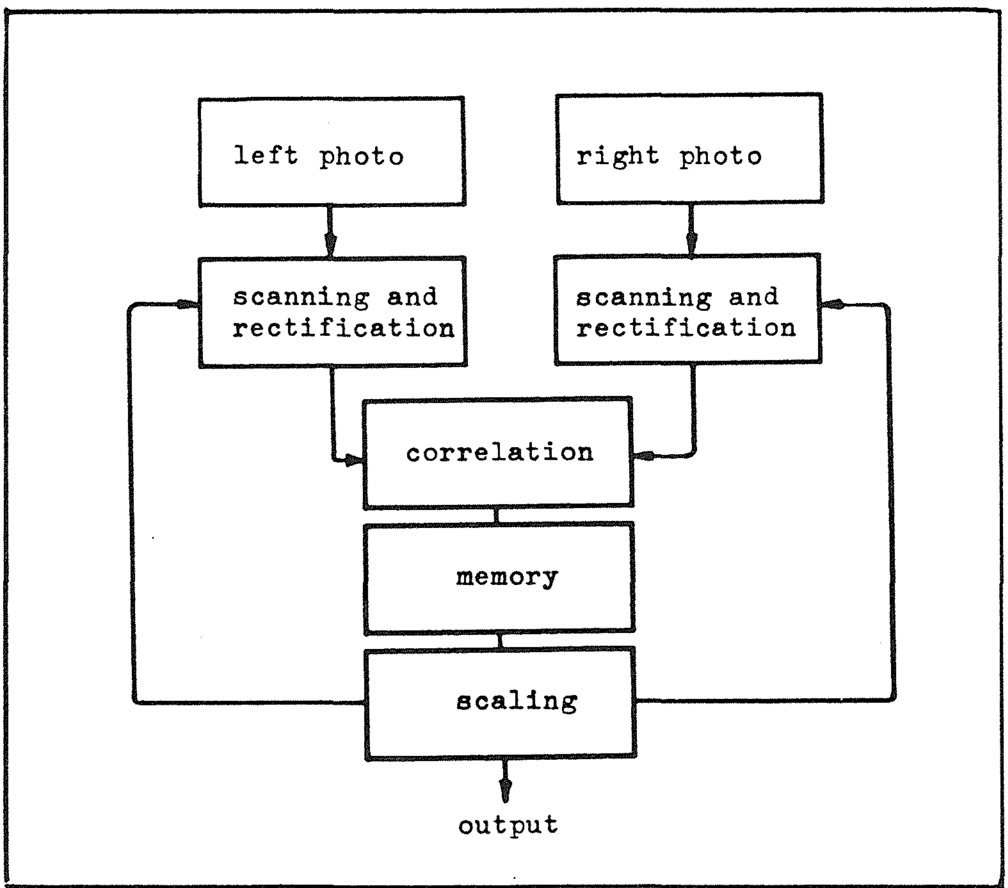

Fig.5: Principle of a correlator with electronic rectification

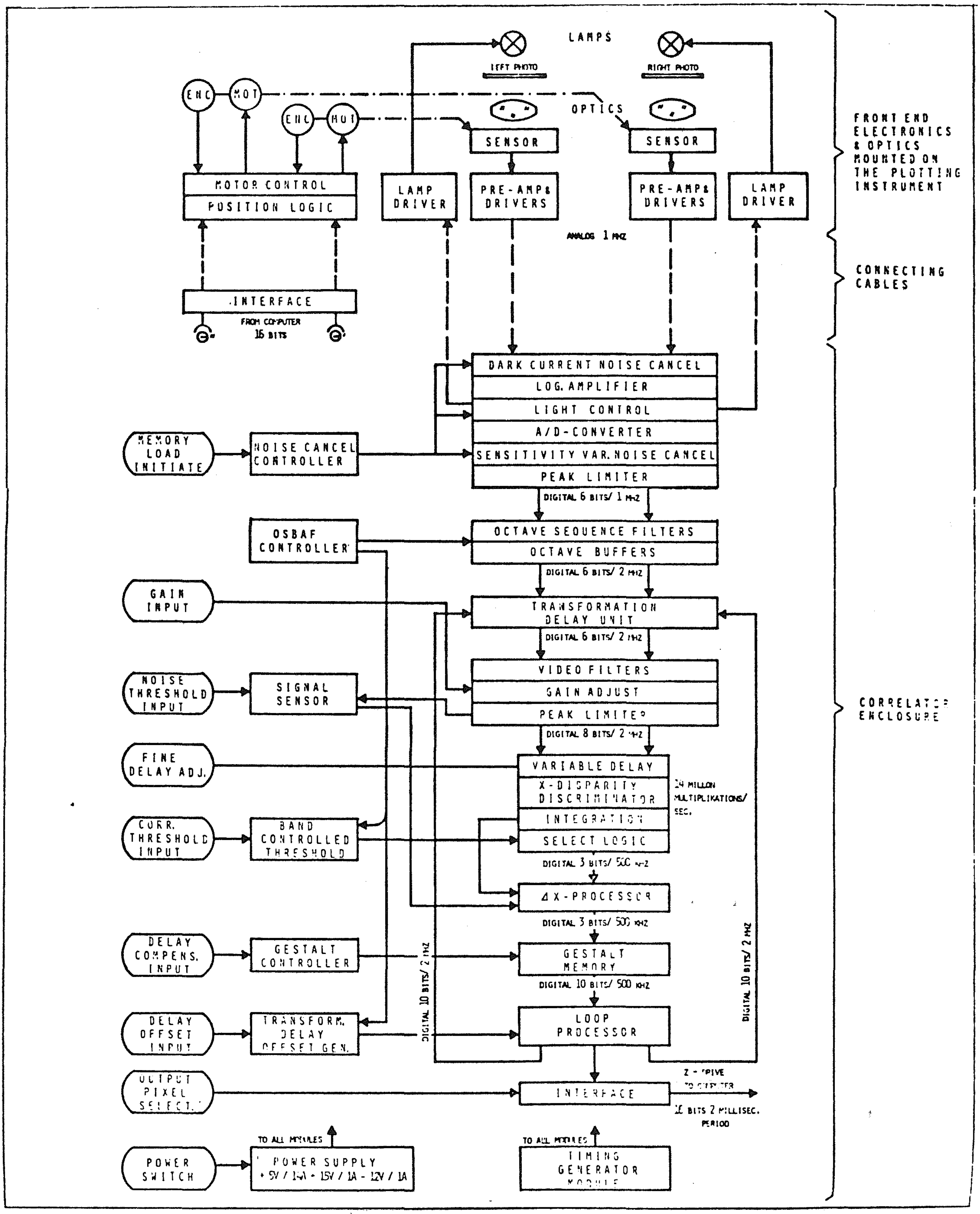

Fig.6: Block Diagram of the Rastar Correlator

3. Electronic Correlation Devices

3.1. Electronic Analog Correlation

The history of electronic correlation is depicted in table 1. The first historical developments concern electronic analog correlation devices.
Only the more recent correlation devices contain digital elements:

3.2. Electronic Digital Correlation

The Bendix AS-11-BX, the Gestalt Photomappers and the Jenoptik Oromat already contain such digital correlation elements. But in particular the Rastar-Correlator, developed at the IPI-Hannover since 1976 is a fully digital correlation system.
After a simultaneous exposure of 1728 image elements with an exposure time of 2 ms the electric charges corresponding to the exposures are transferred to a CCD and transmitted in series digitally to memory. CCD-chips are linear arrays located on rotable servo-controlled mounts. In this way the diode-arrays may be turned into the epipolar direction, which is continuously calculated from image coordinates in the restitution computer.

A certain photometric correction of the signals is performed partially before, and partially after digitization. In particular this concerns errors due to deviations in transfer characteristics of the different photo-diodes of an array and contrast enhancement in photo areas of high density with logarithmic transfer.

Rectification, filtering, correlation and composition of parallaxes obtained by various frequency bands is performed in various digital circuits designed for the purpose to derive a parallax curve over the extent of the 12 mm photo-line-width. Universal circuits can only be used infrequently, because of the high speed requirement necessitating 200 computer operations per µs to conclude a correlation computation for an epipolar line combination in 2 ms. The special circuits can be housed in a 19 inch-cabinet of 2 height units (88 mm).
The development of the Rastar-correlator was brought to a first conclusion with a functional demonstration in 1979. Presently further modifications and improvements to adapt for various applications are being made (see Fig.6).

4. Other Experimental Attempts for Image Correlation

4.1. Optical Correlation

The fact that image correlation may also be achieved by maximal cross-correlation of the Fourier-spectra of two images has been demonstrated by coherent optical procedures which can easily generate a Fourier spectrum directing a laser beam through image portion.
Krulikoski of the Bendix Corp. demonstrated the first success

generating elevation profiles by optical correlation.

Balasubramanian was able to build a coherent optical correlator, based on optical correlation principles using heterodyne techniques.
Inherent to optical correlation is a relatively easy parallel access to frequency information. A handicap, however, is the limited control capability during the evaluation process. In particular rectification within the correlation window is not possible. For that reason optical correlators do not reach the performance required for height measurement.

4.2. Digital Off-Line Correlation

Table 2 summarizes the past digital attempts to correlate image information which has been scanned and stored.

As can be seen from the table most attempts have been made in the last few years. The reason for this may be increased computer capability in speed and storage. But still off-line correlation seems to be much too expensive for utilization in medium sized photogrammetric plants, particularly if there is a need for specialized computer systems with very fast processors for off-line correlation. Because the costs of fast standard computer time and of memory size are still rapidly going down in contrary to the cost of specialized hardware, off-line correlation may eventually in the near or far future become competitive to on-line correlation with respect to comparable accuracy and reliability requirements. This will happen when mass storage becomes inexpensive enough to store the total information from the photos; or it may happen, when methods of preprocessing are developed, which scan the photo information selectively in the manner of an operator who assists an on-line correlation system coming into trouble for some reason.

5. Conclusions

Looking at the reviewed correlation techniques and devices the following general conclusions can be made:

1. Image correlation becomes more and more feasible in photogrammetry.

2. In the near future on-line correlation will dominate over off-line correlation in photogrammetric production.

3. Attempts in evaluating off-line correlation systems are made with increasing effort. Economic application in photogrammetry depends on progress in computer developments.

Table 1: Evolution of On-Line Correlators for Automation in Photogrammetry

year	device name	manufacturer	photo-sensing	rectification within the correlation window	filtering	size of correlation window	method of parallax detection
1958	Stereomat I	Photographic Survey Corp. Toronto, G.L.Hobrough	flying spot random scan	none	analog		
1962	Automatic Map Compilation System	Ramo-Woolridge		none		1,27x1,27 mm2 to 5,08x5,08 mm2	
1962	Automatic Stereo Mapping System	Ramo-Woolbridge (Bunker Ramo)	Nipkow-disc	mechanically linear			orthogonal cross correlation analog
1963	Stereomat III (II?)	Hunting Survey Corp. Toronto, G.L.Hobrough	flying spot epipolar lines	analog linear	analog		
1963	Projection Stereo Plotter AP-14	Librascope Div./Gen. Precision Inc.	flying spot rosette	linear		automatically controlled by terrain slope	
1964	Stereomat IV	Benson-Lehner	flying spot	linear analog	analog	variable with automatic control by correlation quality	Maximum of cross correlation
1966	Universal Automatic Map Compilation Equipment (UNAMACE)	Ramo-Woolridge	TV-raster 128 lines		7 octav bands		
1966	AS-11-B AS-11-C	Bendix	flying spot random scan			automatically controlled by correlation function	orthogonal cross correlation, digital
1968	Stereomat A 2000	Raytheon Automatic	flying spot random scan				
1968/70	ITEK EC-5	ITEK	flying spot diagon. raster		several bands analog		
1970	Gestalt Photomapper	G.L.Hobrough	flying spot in epipolar lines TV-raster 8x9 mm	high degree	6 octav bands	inversely proportional to degree of rectification	orthogonal cross correlation
	OroMAT	Jenoptik	flying spot, deformed TV-raster	longitudinal and lateral tilt	3 frequency bands, analog	3 raster sizes 4 x 4 mm 3 x 2 mm 2 x 1 mm	orthogonal cross correlation, digital
1978	AS-11B-x	Bendix	Laser with rotating prisms, epipolar lines	polygon with maximal 58 corners, digital	digital	3 sizes	
1980	Rastar	Hobrough/ IPI-Hannover	linear photodiode arrays, epipolar lines	polygon with 256 corners, digital	7 octav bands, digital	0,08...5,4 mm	maximum of correlation function

Table 2: Digital Off-line Correlation

year	name	realized by	input	correlation algorithm	remarks
1964	DAMCS	Sharp et al. IBM	resampled rectified digitized photograph	correlation coefficient maximized	demonstration of orthophoto and contour output
1974	UCL-System	Dowman	scanned in epipolar lines on CP1-AP/C digitized photo	cross-co-variance correlation coefficient error function square err. function quotient err. function	experimental, less expensive and less sophisticated method
1974	DIMES	Gambino et al.	raster scan digitized photo	peak of correlation function 2-dimensional	array processor for handling high speed demands
1974	UNB-System	Masry	scanned in epipolar lines digitized photo	"an algorithm"	experimental
1975		Keating et al. (Univ.of Maine)	close to flight line scanned raster digitized photo	euclidean difference, normalized encl.diff., norm.cross correlation coeff., Hadamard transformation	2-dimensional for orientation 1-dimensional for final scan
1976		Kreiling	raster scanned digitized photo		
1977		Göpfert	raster scanned digitized photo	peak of: autocorrel.coeff. cross " " auto " intensity cross " "	comparison for best correlation results of algorithms
1978		Konecny et al.	Scanned in epipolar lines (by preprocessor) digitized photo	peak of cross-correlation coefficient	suggested experimental system
1978		Girard (Etablissement Technique Central de l'Armement Arcueil, France	resampled rectified digitized photo	peak of cross correlation coeff. no geometric rectification in correlation window	experimental
1978		Panton CDC	raster scan oriented to flight direction digitized photo	peak of correlation function	demonstration of contour, 3 D and rectified grid output
1979		Macarovic			in preparation for ISP Congress 1980

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