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INSTRUMENTAL REALISATION AND CALIBRATION OF DIGITAL CORRELATION WITH THE PLANICOMP

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1. INTRODUCTION

The fundamentals of the equipment configuration for digital on-line correlation with the analytical plotter Planicomp have been presented by ACKERMANN , PERTL and GÜLCH (Ref. 1,4,2).

The major area of application is to be found in the photogrammetric stereo measurement process. The conventional parallax measurement of the operator can now be carried out computationally by means of high precision least squares matching (LSM), of small digitized image windows. In this way the quality of the measurements becomes independent of the individual operator and remains uninfluenced by symptoms of fatigue, i.e. subjective influences on the measurement are excluded.

The digital recording of the analog image of an object takes place on-line in the analytical plotter by means of two CCD video cameras, which provide two digital grey value images for the correlation process due to the distribution and intensity of light, passing through the images, within the scanned image windows.

By integrating correlation into the photogrammetric evaluation procedure errors of the electronic digitized image appear in addition to those errors of the photogrammetric image caused by the taking and developing of the image etc..

Besides the geometric connection of the digital correlation with the analytical plotter the task now consists in recognizing errors in the digital data recording, in tracing these back to their causes and correcting them by means of suitable calibration methods.

For this reason, therefore, in addition to the instrumental realisation of digital correlation, applied calibration procedures, investigations and personal experiences with the hardware are subject of the following considerations.

2. SYSTEM DESCRIPTION

Our equipment system for digital on-line image correlation consists of two components. The analytical plotter Planicomp C 100 with HP 1000-F processor and standard software forms the basis (Ref. Fig. 1). The second component is the equipment system for the digitization of images. The main part consists of two CCD video cameras each with its own control unit and monitor. The connection between the two components is established via the optical light paths of the right and left photo-carriage of the Planicomp and via the HP 1000 computer in order to establish the connection to the photo-carriage coordinate system.

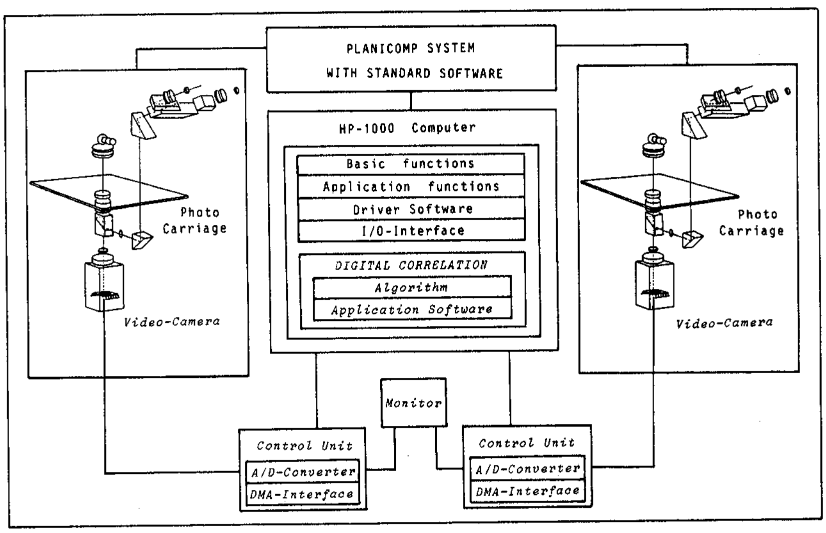

Fig. 1: Equipment system for on-line correlation

In paragraph 2.1 the individual parts of the expanded Planicomp system are described.

Due to the fact that the digital video camera is not widely used in photogrammetry its mode of operation is discussed in greater detail in paragraph 2.2.

2.1 Hardware configuration

The description of the extended Planicomp system encompasses on the one hand the alterations and additions to the Planicomp itself necessary to establish the hardware connection, and on the other hand, the equipment for digitization including the accessories. Of particular interest in this case is the video camera with its sensor.

2.1.1 Planicomp

The optical paths for the digital data recording are integrated in such a way into the optical light paths of the analytical plotter that conventional stereo measurement by the operator and scanning with the digital camera are possible simultaneously without causing any mutual interference (cf. Fig. 2).

Instead of a prism, which diverts the light having passed through the glass-plate and film onto the measuring mark and the eyepiece, a beam splitter is built in, which taps 15% of the light for digital data recording, directing it through onto the camera lens. The camera itself is attached to the frame of the Planicomp, i.e. the camera is stationary and the object the photograph on the photo-carriage, is mobile.

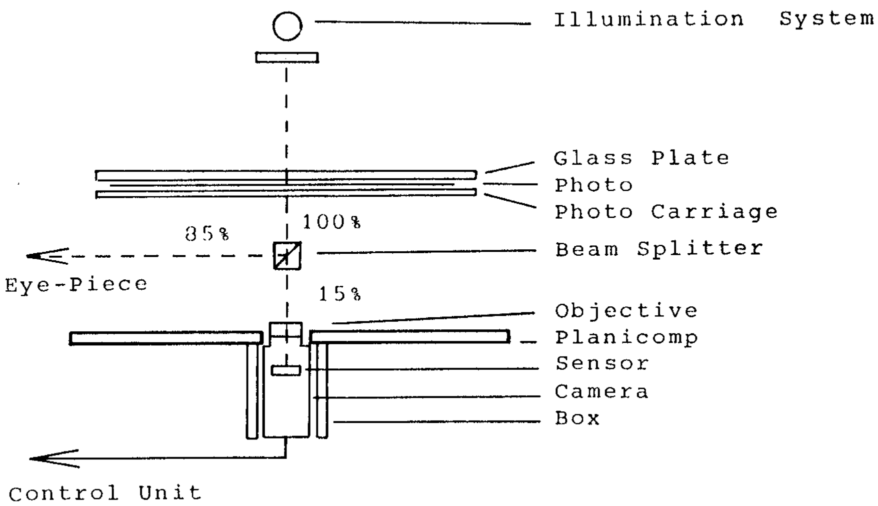

Fig. 2: Light path for digital data recording

2.1.2 Camera

The camera is a black and white CCD (Charge-Coupled-Device) video camera of type C1000-35 M, produced by the Hamamatsu Company. It has a matrix sensor out of light-sensitive semiconductor elements with a spectral sensitivity of 400 nm - 1050 nm, whereby the maximum lies between 800 nm and 900 nm.

There is no pick-up tube, nor are there any movable mechanical parts, as widely found in digital photographic equipment. The solid state technique of the CCD camera makes a compact construction (48mm x 62mm x 131mm) possible with minimal weight (0.5 kg.)

The lens was manufactured separately and has an enlargement factor of 1.35 for the projection from the object plane (image plane of the Planicomp) onto the plane of the sensor array.

The camera function with a diaphragm which is permanently open, i.e. there is no lens shutter. The division between two images which follow each other does not take place mechanically, but instead by means of the electronic selection procedure of the sensor.

Each camera has a C1000 control unit consisting of the analog digital converter M1004 A and the DMA (Direct Memory Access) Interface M999-07, as well as a HP-Interface 12566 B.

2.1.3 Sensor

The two-dimensional array of the Hitachi He 97211 sensor consists of 256 x 320 sensor elements which are set together in the form of a matrix (ref. Fig. 3).

The first and last twelve horizontal lines give incorrect results. Due to the interface only the central 256 of the 320 (H) horizontal pixels can be addressed. The sensor elements consist each of a square light-sensitive area of the dimension 21.6 µm x 21.6 µm. The distance between the centres of the two pixels in both horizontal and vertical direction is 27 µm. The non-active area serves to isolate the pixels from one another.

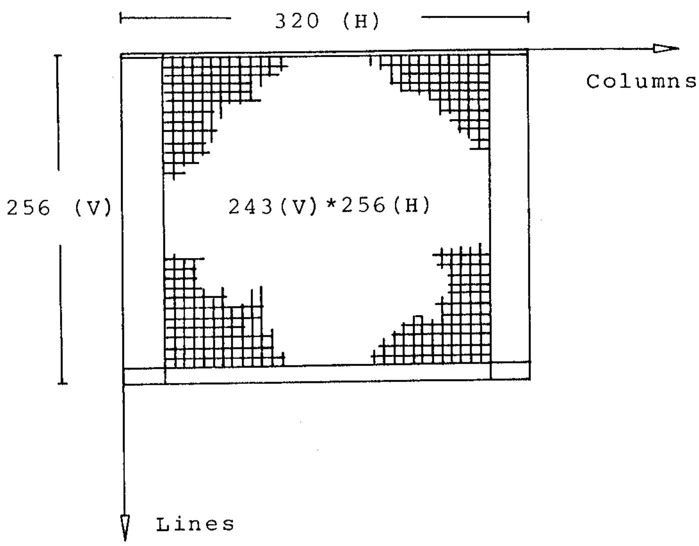

Fig. 3: CCD-Matrixsensor

Due to the optical enlargement the sensor period, subsequently to be called pixel size, becomes reduced in the image to approximately 20 µm, whereby we are able to record with the sensor an area of approximately 4.9 mm x 5.1 mm in the image.

The geometric resolution of the sensor has a limited band width. If two sensor elements fall onto a pair of lines, the theoretical limit of resolution, the so called Nyquist frequency, has then been reached. For this particular sensor it is approximately 25 LP/µm in the image. Up to the present day no investigations for the modulation transfer function have taken place.

2.1.4 System-conditioned disturbing factors for digital data recording

As a result of the connection with the CCD video cameras some problems arise when working with the Planicomp, which, however, are of subordinate importance for the conventional stereoscopic measurement carried out by the operator. With the recording of digital data dust, scratches and other disturbing factors on the film and glass surfaces come to the fore.

Such factors are no great hinderance for an operator when making a stereo measurement. He can recognize the disturbance as such and then react accordingly. Should the disturbance occur at a particular place, it is then as a rule only the case in one image, whereby the stereoscopic impression is not disturbed to any great extend, since the operator works with a large visual field.

Such disturbances, however, exert a direct influence on the correlation of two image windows, in that they either falsify or prevent the correlation. Only by means of complicated algorithms and with certain restrictions would the computer be able to recognize these disturbances and to react accordingly, alternatively the operator would have to intervene and help out with his knowledge.

It is, therefore, advantageous to ensure that the film and the glass surfaces are as dust-free as possible right from the initial stages of preparation. For this purpose there are special aids at one's disposal, such as those which are also used in photographic laboratories. Such substances in liquid form are unsuitable for our purposes, one can alternatively use anti-static hand-brushes, or even better ionised compressed air to clean the film and the glass surfaces.

2.2 Recording of digital data

The light which falls onto the camera lens via the optical path when taking a picture (cf. Fig. 2) is digitally recorded by the sensor according to its distribution and intensity. The resulting video signals are quantized in the control unit and the thereby calculated values are transferred into the computer.

The digital image of the sensor is present in the computer as the end product in the form of natural numbers. The various steps for the recording of digital data, scanning, digitization and data transfer, as well as the decoding are each presented individually. Paragraph 2.2.4 gives a summary of the time expenditure necessary for each of the individual processes.

2.2.1 Scanning

The scanning procedure is that of a static sensor scanning, i.e. the sensor is fixed relative to the object which is projected onto the sensor array. Electrical charges, which are linearly dependent on the incoming light and exposure time, the so-called integration time, are simultaneously built up in the individual sensor elements of the CCD-columns. At regular intervals these electrical charges are transferred parallel into shift registers from which they are subsequently serially selected.

In this way a discrete voltage signal is obtained for each sensor element and each exposure period, the level of which is characteristic for the brightness of the object element.

The serial Pixel-Reading-Frequency is 6.036 MHz. A horizontal line of the electronic image is selected within 63.6 µsec with the line frequency of 15.72 KHz. An image (frame) is built up out of 256 lines which can be visually presented on the monitor. The frame frequency is 60 Hz.

2.2.2 Digitization and Data Transfer

There are two possibilities open for digitization and data transfer, namely the Single Sampling Mode (SM) and the Multiple Sampling Mode (MM). Digitization takes place column by column. The position of the column within a line signal is fixed by means of a counting frequency, not, therefore, by the discrete sensor element. Vertically the pixels are provided by the sensor elements.

In the Single Mode the voltage is measured at a certain position of the line signal and is quantized in 1.5 µsec into 8-Bit grey levels. The grey values 0 and 255 correspond to the colours black and white respectively. In the Multiple Mode the intensity per line signal is quantized not just at one, but at 16 points.

In order to make best use of the transfer rate two consecutive 8-Bit grey values at a time are packed into a 16-Bit word. The digitized information of an image with 256 scanning lines in the buffer (SM: 128 words, MM: 2048 words) is transferred sequentially word by word into the computer by means of the DMA-Interface. The computer receives the digitized and coded video data, discards the values of the first and last twelve lines and stores the remaining data in its memory.

Afterwards the computer selects a new starting address for the sampling procedure, normally increased by 1, and the process begins anew.

There are 16 starting addresses available for the Multiple Mode, and 256 for the Single Mode, i.e. in order to completely digitize the entire sensor array the sampling process has to take place 16 times in the Multiple Mode and 256 times in the Single Mode. It is, therefore, neither in the Single Mode nor in the Multiple Mode possible to directly digitize a central window of the sensor, but one is always forced to digitize and transfer complete CCD-columns and to extract the required lines in the computer afterwards.

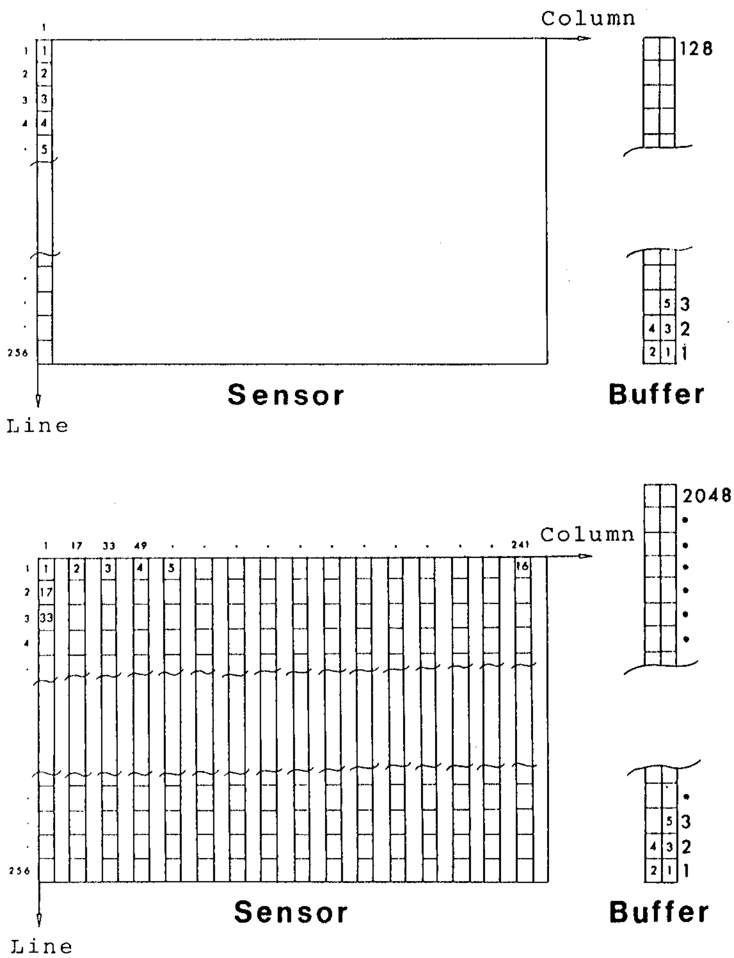

Fig. 4: Single and Multiple Sampling Mode

2.2.3 Decoding

After the data transfer has taken place there are 243 x 256 grey values present in the memory in coded form. Decoding takes place with the help of bit-shifting and bit-masking. For an arbitrary window one obtains the grey value for each pixel and then via the discrete sensor element the related line and column coordinate. These basic data form the basis for the digital correlation procedures with the Planicomp.

2.2.4 Time expended for the data recording

a) Total sensor of 243 x 256 pixels
   For the scanning, digitization and the data transfer of an entire sensor array we require 8.53 seconds in the Single Sampling Mode and 0.53 seconds in the Multiple Mode. In order to decode the transferred values from the Multiple Mode approximately 0.3 seconds are required for the entire sensor, i.e. the data recording of a camera in the Multiple Mode lasts approximately 3.5 seconds up to the completed preparation of the grey values in the EMA (Extended Memory Area) of the HP 1000.

b) Central window of 32 x 32 pixels
   At the moment we provide two grey-value matrices of the size 32 x 32 pixels for the correlation of small image windows. For scanning, digitization and data transfer in the Multiple Mode 1.06 seconds are required, 0.22 seconds for the decoding, so that after a total of 1.28 seconds the correlation of the two windows can commence.

c) Acceleration
With a certain memory configuration of the computer and in the case of scanning taking place with both cameras, so that, for example, correlation is not carried out with an artificial mask, there is a possibility to further reduce the time required for scanning, digitization and data transfer. By using the SAM (System Available Memory) as an intermediate buffer data recording becomes possible in a parallel manner with both cameras. First the left and then the right camera is addressed.

With this so-called Class I/O the time from scanning up to and including transfer in the Multiple Mode is reduced to 0.3 seconds per array. A considerable acceleration of the decoding procedure by a factor of 3 can be attained by programming in Assembler instead of Fortran IV.

The time for the data recording of an entire array using Class I/O and Assembler decoding can be reduced from 3.5 seconds to approximately 1.5 seconds. For two windows of the dimension 32 x 32 pixels only 0.67 seconds are required instead of 1.28 seconds.

3. CALIBRATION

The most important task of calibration is the establishment of a geometrical relationship between the Planicomp photo-carriage coordinate system and the sensor systems of the two cameras. Only then is the integration affected of the digital correlation into the analytical plotter and into the subsequent photogrammetric analytical processes.

Before commencing any investigations a general check is carried out with regard to breakdowns or other hardware errors in order to ensure that the electronic component parts for digital data recording function correctly.

Besides these aspects calibration consists amongst other things, of procedures whereby characteristics of the sensor can be ascertained, such as summarized by HOFMANN (Ref. 3) by the term image quality. In this way it becomes possible to carry out corrections not only geometrically, but also radiometrically when dealing with deviations from the norm.

3.1 Basic sensor check

At present the check carried out to ensure correct functioning comprises also, in addition to the sensor array, where individual pixels could cease to function, various electronic basic functions of the control unit. In this way the A/D conversion, digitization and quantization are checked with regard to known peculiarities or sources of error.

3.1.1 Blemishes

Already during the manufacture of the sensor arrays blemishes of individual pixels or groups of pixels can occur through dust or corrosion errors. With the aid of an analysis of the grey value distribution over the entire sensor the critical zones can be detected using varying lighting and an object of uniform transparency. The search for such failures is important in order to enable corrections to already be carried out during the image pre-processing. Defective pixels or smaller areas can be furnished with the mean grey value of their surroundings and in this way they do not present any disturbing factors for the subsequent correlation procedures.

3.1.2 A/D conversion-saturation

A special effect, which normally only occurs with saturation of the sensor and with digitization in the Multiple Mode, is the formation of echoes of very bright signals within a line. The term saturation means that the voltage of the signal exceeds the voltage value for the grey value 255. Now the problem is that this echo effect is not visible on monitor, but only occurs in the digitized and transferred image.
In Fig. 5, a numerical representation of the grey value matrix, two echoes of the scanned fiducial mark can be very clearly seen. Because of a defective condenser, which was not discharged in time, this echo effect occurred with one of our cameras even without saturation.

Information becomes lost with saturation as the grey values cannot exceed the value of 255. In addition, a pronounced blooming effect can be observed with very bright objects.

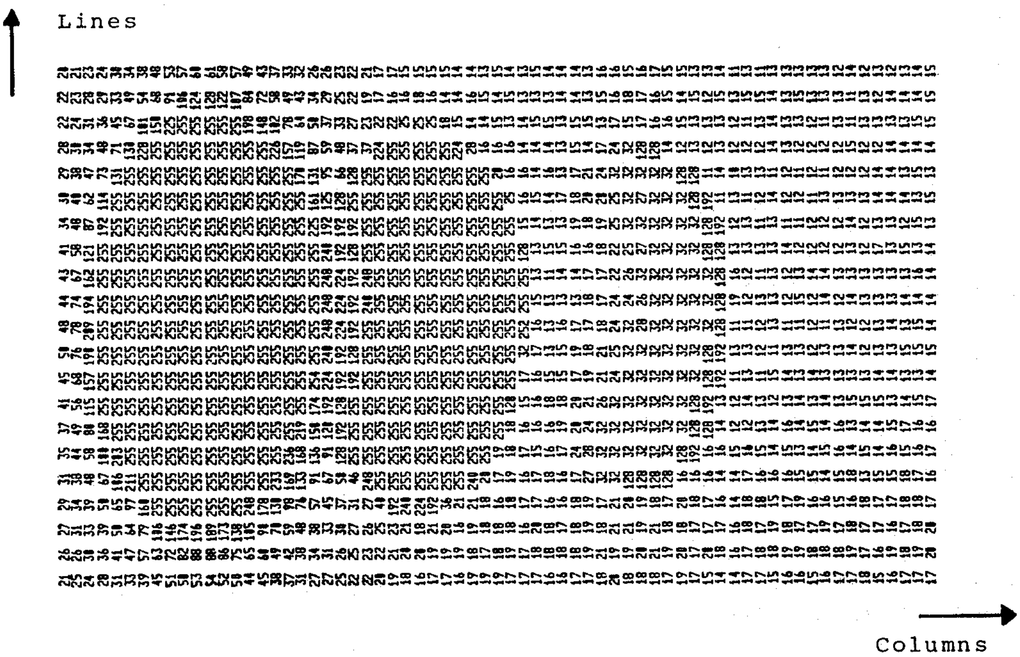

Fig. 5: Scanning of a fiducial mark with saturation and resulting echoes

Because of these reasons it is indispensable to provide for a safeguard against saturation. This can take the form of either software or hardware or be a combination of the two. With regard to semi-automatic or fully automatic application (e.g. DHM-measurement) one can consider the possibilities of a computerized automatic lighting arrangement.

3.1.3 Quantization

By quantization the voltage signal in the control unit is discretized into 8-Bit grey levels. Hereby in addition to the random errors of discretization a systematic quantization error with one of the cameras occured in our system. Due to the failure of one of the bits it was not possible to obtain all the grey values between 0 and 255. As can be seen in Fig. 6 there is always a group of four grey values which is not represented. Each of the missing grey values was then given the grey value which followed the group.

Gray-Value	Number	
159	26	
160	0	
161	0	
162	0	
163	0	
164	239	<--- Accumulation
165	45	
166	49	
167	21	
168	0	
169	0	
170	0	
171	0	
172	306	<--- Accumulation
173	256	
174	379	
175	282	
176	0	
177	0	
178	0	
179	0	
180	3915	<--- Accumulation
181	1867	
182	2591	

Fig. 6: Section of a histogram showing the distribution of the grey values

By applying grey value histogram analysis this error could be detected and fixed.

3.2 Radiometry

In the foreground here is the connection between optical density and digital grey value, i.e. the quantitative measurement of light intensity.

The distribution and intensity of the grey values in the digital image is dependent upon the scanned analog image and upon the hardware system itself. With regard to the distribution of the grey values one can observe a marked decrease in brightness towards the boundary (see 3.2.2). In addition the lighting intensity and thereby the grey values are subjects to large fluctuations due to unstabilized lighting (3.2.3). This effect is reflected most notable in the information about sensor noise, which is compiled in paragraph 3.2.4.

3.2.1 Quantitative light intensity measurement

Even if one disregards the maximum brightness of fiducial marks, there occur regionally many and often very large differences in brightness. These differences do not disturb the human observer to a great extent. In many cases it is not necessary for him to readjust the brightness.

In contrast to this the sensitivity range of the camera is smaller. Fig. 7 illustrates the result of an optical wedge measurement using a camera with maximum lighting. The grey value, in this case the mean value of a window measuring 32 x 32 pixels, is plotted in relation to the optical density of the respective optical wedge step.

For the steps 1-6 (low density) the sensor is saturated and yields the grey value 255. After this comes an area in which the grey value drops from 255 to 35 within 5-6 optical wedge steps. Within this area the sensor reacts very sensitively to the slightest changes in density. With a density of 2.0 and upwards and with changes in the density of constant size only minimal changes in the grey value area are captured. This means that information gets lost thereby within this area because the quantization in the grey values is too coarse. Here, too, the sensor noise makes itself noticeable to a large extent (cf. 3.2.4).

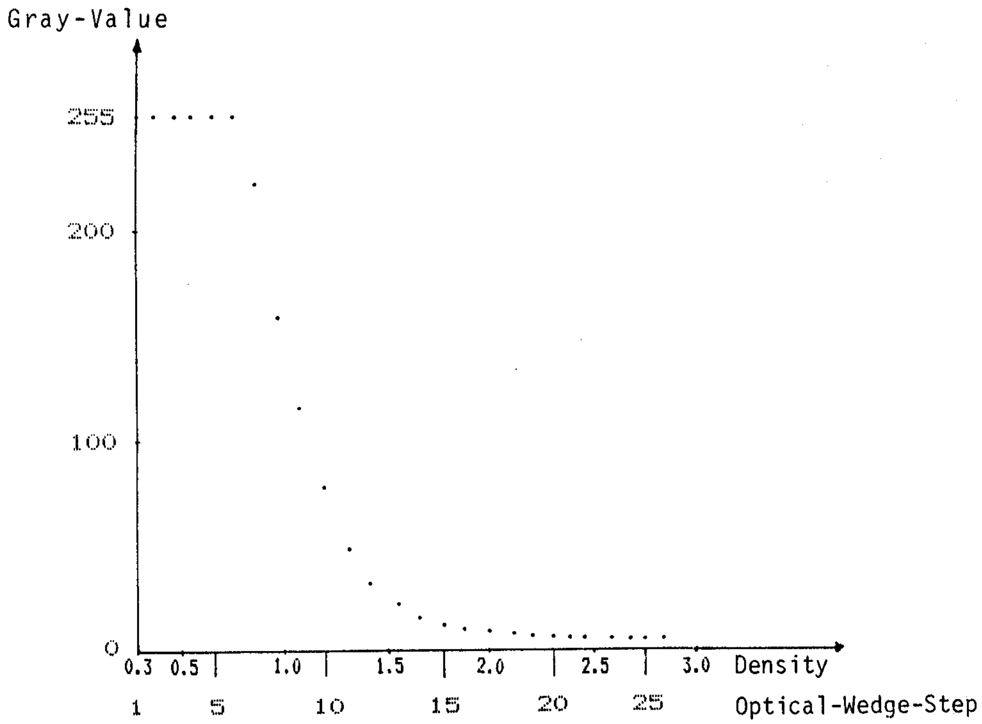

Fig. 7: Optical wedge measurement

The density range favourable for the camera is around 0.6 density steps. As the density range is larger in many images one endeavours to find in each case the optimal lighting for the chosen window, in order to prevent information loss and to obtain results which are as exact as possible.

It has been shown that the precision of digital correlation is independent of the lighting to a very large extent, so long as neither saturation nor undermodulation takes place. The favourable grey value area lies between grey value 25 and 250. Should the lighting decrease further, then the correlation precision worsens by the factor of 2 to 4.

3.2.2 Distribution of grey values on the sensor

The grey values on the sensor are not distributed evenly when using a homogeneous object. The influences most notable are the mutual position of sensor and lighting, the cone of radiation of the lighting, and effects present at the boundaries of the optics and sensor.

In Fig. 8 the isolines of the grey values are illustrated for a window of the dimension 240 x 240 pixels (from the programme SCOP). The scanned object was the photo-carriage of the Planicomp, a homogeneous surface above the window with an almost constant optical density. The distribution of the grey values is in the form of a paraboloid, whereby the centre of maximum brightness is clearly asymmetrically shifted in the line and column direction. The maximum difference between grey values is approximately 30-35 grey levels. In addition one can also see two dark areas which originate from local impurities.

This decline in brightness only disturbs the correlation of small image windows from the central area of the sensor to a minor extent; this effect should however at any rate be corrected for other tasks, where the entire array is used, for example the automatic fiducial mark search.

In this way compensating correction areas for all grey values can be calculated for various degrees of lighting by using an object of uniform transparency. Thus a radiometrical correction as regards the brightness distribution can be made dependent upon the grey value for each pixel or at least each subregion of the sensor by using additional interpolation between the surfaces.

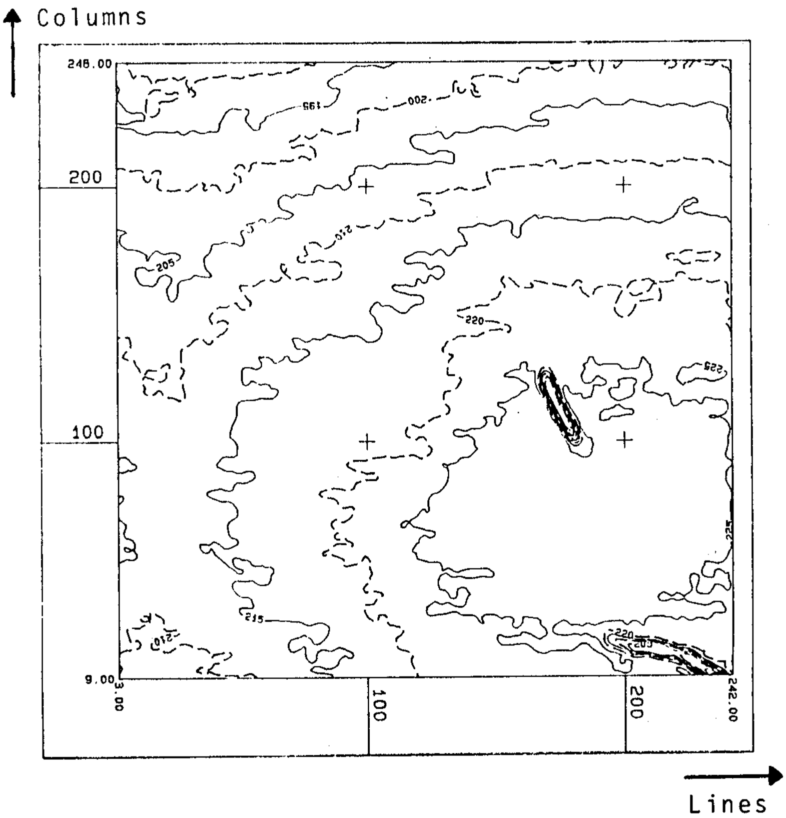

Fig. 8: Isoline illustration of the grey value distribution

3.2.3 Influences of lighting - changes in voltage

The lighting system of the Planicomp is not of constant voltage. The halogen lamps and in particular the potentiometer to regulate the lighting are sensitive to changes in the voltage.

In several measuring epochs lasting between 1-2 hours numerous grey value jumps of up to 30 grey value steps were noted. During one test the left lighting system was stabilized by an external power supply. The right lamp received its power supply from the Planicomp. Scanning took place alternately with the left and right camera and finally the grey value of one pixel was plotted above the time. Two large changes in the voltage occurred during this period, which can be very clearly seen by grey value jumps in Fig. 9.

On the other hand, however, nothing of this kind could be ascertained with the lighting of stabilized voltage (cf. Fig. 10). This curve runs altogether much more smoothly and is almost horizontal.

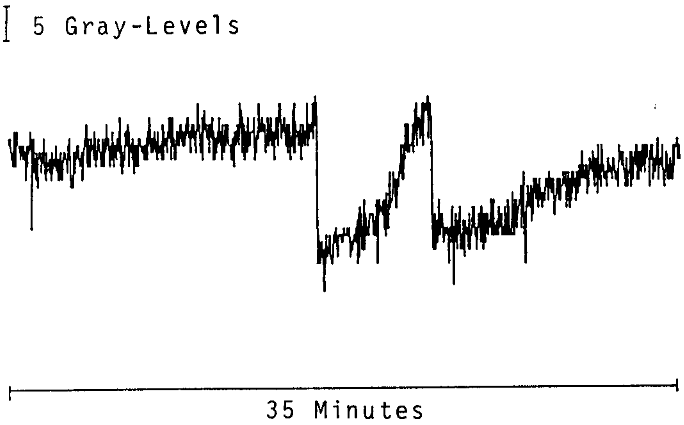

Fig. 9: Change in the grey value when measuring without stabilized lighting

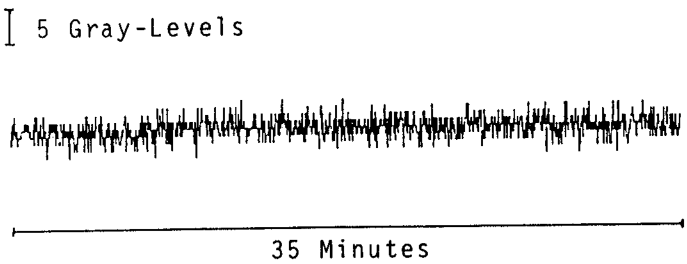

Fig. 10: Change in the grey value when measuring with stabilized lighting

Due to the unforeseeable and furthermore numerous jumps it can be stated that lighting of constant voltage is indispensable.

3.2.4 Sensor noise

For each group of 100 measurements the standard deviation of the grey values dependent upon the brightness was determined for the pixels of a window measuring 32 x 32 pixels.

Fig. 11 tabulates the minimum, maximum and mean grey value of the measurements of the window when using varying lighting, and also the minimum, maximum and mean standard deviation, respectively.

MEAN {GV}			SDEV {GV}		
Min	Max	Mean	Min	Max	Mean
239.3	249.0	243.8	1.5	2.4	1.9
162.6	168.5	165.2	1.5	2.3	1.8
116.4	120.9	118.4	1.2	2.0	1.5
67.4	70.5	68.8	.8	1.7	1.2
42.1	44.3	43.2	.8	1.5	1.1
25.8	27.7	26.9	.7	1.5	1.1
15.6	17.3	16.5	.5	1.4	.9

Fig. 11: Standard deviation of grey values using variable lighting

It can be clearly seen that the standard deviation is dependent upon the grey value.The mean standard deviation of the grey values of a homogeneous surface of maximum brightness is 1.9 grey levels . In the grey value range of 25 -30, which is still suitable for correlation, the standard deviation is approximately 1.1 grey levels.

The aim of a second investigation was to gain information about the dispersion of the grey value differences in the direction of x and y and also about the differences between consecutive measurements.

In this connection the investigation also served to test the effect of lighting of constant voltage.

Once again a central 32 x 32 window with a mean grey value of 200 was the object of our investigations. The results presented in Fig. 12 illustrate a mean value for all measurements taken from various measuring epochs each with between 500 and 2000 samplings.

SDEV {GV} of	Without Stab.	With Stab.
- Gray-values	1.7	1.4
- Gray-value differences of suceeding samplings	2.7	1.9
- Gray-value differences in x-direction	2.4	1.7
- Gray-value differences in y-direction	1.7	1.7

Fig. 12: Standard deviations of grey value differences using constant lighting

As was to be expected the standard deviation of consecutive sampling differences with stabilized lighting is larger by a factor of $\sqrt{2}$ than the standard deviation of the grey values. From the standard deviations of the grey value differences it can be concluded that low correlations with $\rho < 0.3$ exist between grey values within the columns and lines, respectively. The variations in the grey value differences of x- and y-direction are one of the causes for the smaller internal precision of correlation in the x-direction which was previously noted by GÜLCH (Ref. 2).

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3.3 Geometry

The most important component of geometrical calibration is the establishment of a geometrical connection from the Planicomp system to the camera system or sensor system. The results of the digital correlation procedures are present in the sensor systems in the form of pixel coordinates and have to be changed into the units of either the photo-carriage coordinate system or alternatively the photo-coordinate system.

The geometrical transformation T is assumed to be:

$$\begin{pmatrix} \overset{1}{x}_i - \overset{1}{x}_{m,i} \\ \\ \overset{1}{y}_i - \overset{1}{y}_{m,i} \end{pmatrix} = T^1_2 \begin{pmatrix} & \overset{2}{x}_i - \overset{2}{x}_m \\ P^1_2 \; ; & \\ & \overset{2}{y}_i - \overset{2}{y}_m \end{pmatrix}$$

with:

$\overset{1}{x}_{m,i}$; $\overset{1}{y}_{m,i}$	:	Measuring Mark position in photo carriage coordinates
$\overset{2}{x}_m$; $\overset{2}{y}_m$	:	Measuring Mark position in sensor coordinates
$\overset{1}{x}_i$; $\overset{1}{y}_i$	:	Point i in photo carriage coordinates
$\overset{2}{x}_i$; $\overset{2}{y}_i$	:	Point i in sensor coordinates
P^1_2	:	Transformation parameters Scale and Rotation in x and y

The determination of the transformation parameters takes place in two stages, which are described below.

In addition to the results of calibration measurements, investigations about the stability of the calibration parameters are also presented in paragraph 3.3.3.

3.3.1 Connection Planicomp - sensor system: shift

The connection from the photo-carriage coordinate system to the sensor system is established with the aid of the measuring mark. Like the sensor the measuring mark is fixed. It is not projected onto the sensor with the result that its position of the sensor array cannot be directly determined.

The auxiliary procedure takes place separately for each photo-carriage and consists of several steps:

STEP 1) Setting of a grid cross in the photo-carriage plate by the operator using the measuring mark

A suitable object for the indirect method had to meet the following requirements

- be able to be positioned by the operator with a high degree of precision
- high degree of contrast
- size suitable for the correlation process (2-3 pixel)
- be symmetrical
- be of constant form and size (no object change)

The grid crosses of the photo-carriage plate of the Planicomp meet these requirements with the disadvantage, however, that with an aerial photograph the fixing of the position becomes more difficult due to the background.

STEP 2) Automatic search of the coarse position of the grid cross projected onto the sensor array.

The grid cross projected onto the sensor is sought within a central window of the dimension 80 x 80 pixels by means of object localization methods. The area to be searched is purposefully chosen so large because the grid cross can easily be shifted to a distance 10-20 pixels away from the centre of the sensor.

The search for the object can be divided into three stages:

a) The 80 x 80 grey value matrix is convoluted with a 9 x 9 mask. As can be seen in Fig. 13, this mask is in the form of a cross with a line width of 3 pixels, such as would approximately correspond to the real object.

0	0	0	1	1	1	0	0	0
0	0	0	1	1	1	0	0	0
0	0	0	1	1	1	0	0	0
1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1
0	0	0	1	1	1	0	0	0
0	0	0	1	1	1	0	0	0
0	0	0	1	1	1	0	0	0

Fig. 13: Mask for object localization

The artificial cross is made up of lines and columns in both vertical and horizontal direction, since the real grid cross is more or less parallel to the axes of the sensor. Convolution means that the mask is shifted pixel by pixel across the area to be searched, that each element of the 9 x 9 matrix is multiplied by the grey value below and that the total sum is then assigned to the central pixel.

b) In order to search for relative maxima a 3 x 3 image window is shifted pixel by pixel across the convoluted grey value matrix. If the central pixel has a larger value than the eight surrounding ones, the grey value remains as before, otherwise it is reset at zero.

c) The absolute maximum is determined from the list of the relative maxima, the coordinates of the former then being implemented in the next step as approximate values.

STEP 3) Determination of the subpixel position by means of correlation with an artificially generated target.

The determination of the subpixel shift results from digital correlation of an artificially generated mask matrix of a grid cross and of a search matrix centered around the coarse position from step 2). The mask is symmetrical, the centre symbolises the position of the measuring mark and thereby the photo-carriage coordinate system. The line-width and the radiometric form of the grid cross were obtained empirically. The grey values of the mask matrix are adapted to the real sampled object.

After step 3 has been completed the coordinates of the centre point of the grid cross are known and thereby the measuring mark in the sensor system.

STEP 4) Multiple repetition of steps 1) - 3), testing and computation of the mean value.

The fixing of the position is carried out repeatedly, and is each time newly set by the operator. The individual results are tested for deviations and then finally the mean value is computed.

The precision of the coordinates is dependent to a large extent on the setting accuracy of the object by the operator (≅ 1-2 µm), as in this case the internal precision of the digital correlation is very high with a standard deviation of $\sigma_{x,y}$ = 0.4 µm - 0.6 µm.

3.3.2 Connection Planicomp - Sensor System: Rotation-Scale

The second step comprises the determination of 4 affine parameters to find out the rotation and scale in x- and y- direction with the aid of automatic simulated grid point measurement.

A grid cross of the photo-carriage plate is moved to 25 positions one after another, which are distributed over the entire sensor. This represents a regular 5 x 5 point grid in the photo-carriage system. At each of the positions the sensor coordinates of the measuring mark are obtained by the method described in paragraph 3.3.1. The search windows for the coarse positioning are, however, in this case considerably smaller.

From the nominal photo-carriage coordinates and actual sensor coordinates of the grid points the 4 remaining transformation parameters can be obtained after adjustment by means of the least-squares method.

3.3.3 Stability examinations

The position of the measuring mark alters within the time span of a day. The coordinate in the horizontal direction, which corresponds approximately to the x-direction of the Planicomp sytem, is affected to a considerably larger degree than the coordinate in the vertical direction.

As described by GÜLCH (Ref. 2) one can observe a marked drift effect in the x-direction after turning on the cameras. One can see from Fig. 14 that the x-coordinates of the measuring mark have altered by approximately 30 µm two hours after the cameras have been turned on.

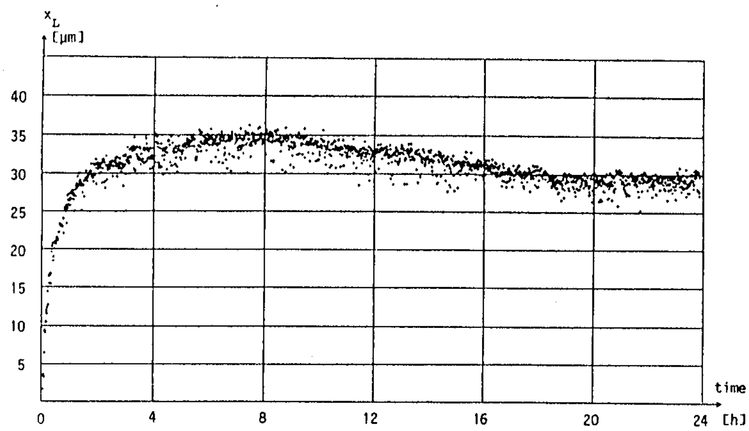

Fig. 14: Drift x-coordinate, left sensor

In order to avoid this drift effect having any consequences for measurements and also to avoid repeated calibration performed within short time periods we work with cameras that are constantly turned on.

The results portrayed in Fig. 15 have been obtained by a test using continuous automatic determination of the position of a fixed grid cross over a period of 70 hours and with simultaneous recording of the temperature. The first curve represents the temperature flow, the x- and y-differences of the coordinates from the initial determination are plotted against the time. As the cameras were switched on for more than 48 hours there is no drift effect to be observed. The curve for the x-coordinate runs with a certain time delay analog to the temperature curve . A change in the temperature of approximately 3.0 degrees caused a change in the coordinates of approximately 0.3 pixels. The y-coordinate is affected by temperature to a lesser extent. The frequency change is only partially responsible for this behaviour. Temperature-dependent mechanical changes in the sensor array, and also with regard to the camera fastening, play a role here, too. Even the photo-carriages of the Planicomp are subject to the effects of temperature; a change in temperature of 1°C can bring about a change in the range of 1 µm in the coordinates. As a result of the construction this can influence the x-direction to a larger extent than the y-direction. Up to now a more detailed quantitative analysis of the curves and a splitting-up into the individual causes has not been carried out.

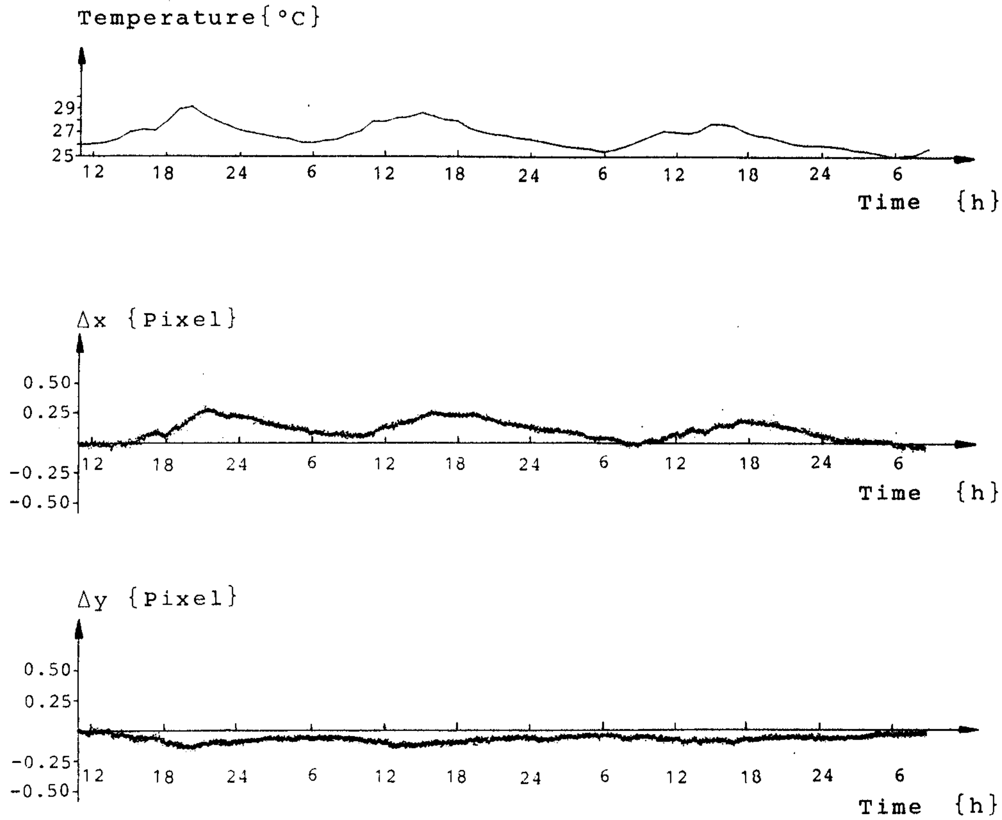

Fig. 15: Temperature effects on continuous measurements

Of importance is the fact that we can presume with normal temperature flow changes in the coordinates of approximately 1-3 μm within a period of two hours (the exception being the drift effect), and that we should, therefore, carry out a calibration roughly within this time interval due to the calibration accuracy.

The determination of the affine parameters yielded the following results for the scale (pixel size) in x- and y- direction for both sensors:

left sensor	Mx = 18.25 (μm/pel)
	My = 19.06 (μm/pel)
right sensor	Mx = 18.10 (μm/pel)
	My = 18.86 (μm/pel)

The differences between the x- and y- direction are clearly noticeable; the results also deviate from the expected pixel size of 20 μm. To a lesser extent the scale parameters are also time-, respectively temperature dependent.

With tests using a 32 x 32 point grid the maximum residuals were in the range of 4-5 μm, with a large proportion of local systematics, which among other things are caused by the movement of the photo-carriage when approaching the grid points; this means a grid can only be conditionally assumed to be nominal.

Over a period of several weeks geometrical calibration was carried out at the same time of day without the cameras being turned off in between times. This shows that the calibration parameters did not alter to any great extent. Maximum changes of 0.4 pixels were recorded for the x-coordinates. At other points in time, however, changes of up to 10 pixels were recorded which were caused by unintentional jolts or other external influences. This fact underlines emphatically the necessity of an at least daily determination of the geometrical transformation parameters.

At present approximately 10 minutes are required for each photo-carriage using the described version, whereby 2-3 minutes are spent on the position determination. As shown by experience smaller search windows can also be used for operational application, and also, if need be, the number of grid points can be decreased to an extent, whereby certain accuracy requirements can still be fulfilled. Employing these measures the total time for the determining of the geometrical transformation parameters could be reduced to approximately 1-2 minutes per photo-carriage.

3.3.4 Sensor geometry

For digital correlation we use two grey value matrices with square, regularly arranged pixels. This is only approximately given by sensor geometry, as the individual sensor elements are put together with certain production tolerances, and moreover there are electronically conditioned differences of the pixels in line and column direction.

Besides the radiometric corrections the aim is also to store geometric correction values for each pixel and to consider them in real time.

This has not yet been realised for two reasons. First of all the question has to be clarified as to whether the correction parameters can be determined with a sufficient degree of accuracy in view of the instabilities when determining the pixels electronically, and if so, to what extent they are subject to time changes.

Secondly, for an operational application storage area should be available for correction parameters pixel by pixel or at least for regional geometric correction parameters, whereby we can only conditionally provide for this with the present computer, in particular with regard to real time correction.

4. CONCLUSIONS

With the establishment of the geometrical connection of the coordinate system of the matrix sensors to the photo-carriage coordinate system of the Planicomp the data recording by means of digital cameras is integrated into the photogrammetric measuring process with the analytical plotter. In this way it is possible to replace the conventional parallax and point measurement of the operator by digital on-line correlation of two image windows, and to then use the results in standard computer programmes.

The described characteristics, special features and error sources of the system were discovered gradually and only partially by systematic searching. The principle of tracing irregularities and exceptions with regard to correlations back to their causes, which often originate from the hardware, proved a success. The investigation of the sensor characteristics has not yet been completed; some effects, which have already been discovered but which are not presented here, are still to be clarified, and suitable counter-measures or corrective methods to be found for them and these then to be integrated into the system.

The knowledge gained so far serves as a basis for the development of various modules of a programme system for the systematic functional test of the cameras and for the determination of radiometrical and geometrical calibration parameters.

Due to ignorance of some problems several measurements using digital correlation (cf. 5,6) did not take place as regards the hardware under the best conditions, so that one can reck on with better results in these cases, too, when excluding error sources and taking into consideration the various correction values of calibration.

To what extent in the foreseeable future radiometrical and geometrical corrections in real time will be able to be carried out regionally or pixel by pixel depends, because of the large storage area requirement and the length of computing time, upon the further development of more efficient processors, which in addition to these tasks will be able to carry out the decoding, correlations and various computer-bound image processing methods with a considerably greater speed.

At present there is much movement on the market for optical semi-conductor sensors with more and more efficient and larger products (eg. HDTV). With the development of matrix sensors with direct access to individual pixels or regions faster access times can be achieved, with the result that the present equipment system for digital data recording with its unexpected high complexity and problematic nature will be replaced in some years time by one of the new generation.

The results of the investigations to data can serve as an additional deciding factor for the selection of new equipment. With the programmes and the experience gained the investigation regarding the characteristics and special features, as well as the search for errors can be carried out considerably more systematically and more purposefully and can be as regards the time expenditure organized more effectively.

REFERENCES

/1/ ACKERMANN, F.: High Precision Digital Image Correlation, Vortrag, 39. Photogrammetrische Woche, Stuttgart, 1983.

/2/ GÜLCH, E.: Geometric Calibration of two CCD-Cameras used for Image Correlation on the Planicomp C100 IAP, Vol. 25-B3, Rio de Janeiro, 1984.

/3/ HOFMANN, O.: Bildgüte aktiver und passiver Abtaster, Bul 51 (1983), Heft 3, S. 103-117.

/4/ PERTL, A.: Digital Image Correlation with the Analytical Plotter, IAP, Vol. 25-B3, Rio de Janeiro, 1984.

/5/ PERTL, A.: Empirische Ergebnisse der automatischen Parallaxen und Punktmessung, Vortrag, 40. Photogrammetrische Woche, Stuttgart, 1985.

ABSTRACT

This paper presents the components of the equipment system for digital on-line image correlation with the analytical plotter Planicomp C100. In particular the recording of digital data by means of two CCD video cameras and their operation modus is described in detail. The working process covers the ground from digitization of images to the preparation of grey-value matrices in the computer as the basis of the digital correlation procedure.

The second part is comprised of investigations, methods and results in respect of the radiometric and geometric calibration of the system. Most worthy of note is the procedure for the determination of the geometrical relations between the CCD matrix sensors and the carriage coordinate systems of the Planicomp for the further use of results obtained by the digital correlation procedure in photogrammetric computer programme systems.

In addition, a report is given on experiences with the system, on particular characteristics and possible weak points in respect of the hardware.

INSTRUMENTELLE REALISIERUNG UND KALIBRIERUNG DER DIGITALEN KORRELATION AM PLANICOMP

ZUSAMMENFASSUNG

Die Komponenten des Gerätesystems zur digitalen on-line Bildkorrelation am analytischen Auswertegerät Planicomp C100 werden vorgestellt. Insbesondere die digitale Datenerfassung mittels zweier CCD-Videokameras und deren Funktionsweise wird näher beschrieben. Der Ablauf reicht von der Digitalisierung der Bilder bis zur Bereitstellung zweier Grauwertmatrizen im Rechner als Grundlage der digitalen Korrelationsverfahren.

In einem zweiten Teil folgen Untersuchungen, Methoden und Ergebnisse zur radiometrischen und geometrischen Kalibrierung des Systems. Wesentlichster Bestandteil ist dabei das Verfahren zur Ermittlung der geometrischen Beziehungen zwischen den CCD-Matrixsensoren und dem Maschinenkoordinatensystem des Planicomp zur Übernahme der Ergebnisse der digitalen Korrelationsverfahren in photogrammetrische Auswerteprogramme.

Ergänzend wird über Erfahrungen mit dem System, über besondere Eigenschaften und mögliche Fehler der Hardware berichtet.

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