GEOMETRIC CALIBRATION OF TWO CCD-CAMERAS USED FOR DIGITAL IMAGE CORRELATION ON THE PLANICOMP C 100

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Abstract: The analytical plotter Planicomp C 100 was equipped with two Hamamatsu CCD array sensors for on-line image correlation. With this correlator x- and y-parallaxes will be measured for the application of digital point transfer. The paper reports on methods, problems and results of the geometric calibration of the system.

0. Introduction

Since 1980 the Institute of Photogrammetry of Stuttgart University is engaged in development concerning high precision digital image correlation and its application in photogrammetry.
After fundamental theoretical (Förstner, 1982) and empirical studies (Ackermann, Pertl, 1983) on digital correlation by matching digitized image windows in connection with the development and programming of an efficient correlation algorithm based on a least squares solution, it became evident that the method is capable of very high precision and shows most promising aspects for practical application. It was, therefore, decided to make digital image correlation operational for practical application by implementing it on available photogrammetric equipment.

The automatic determination of x- and y-parallaxes by digital image correlation has direct application in conventional photogrammetric operations, such as numerical relative orientation, digital elevation models, point transfer for aerial triangulation and deformation analysis. The analytical plotter Zeiss Planicomp C 100 of the Institute was equipped, in 1983, with two Hamamatsu CCD array sensors for on-line image correlation (Ackermann, (1984). Fig. 1 shows a sketch of the hardware configuration.

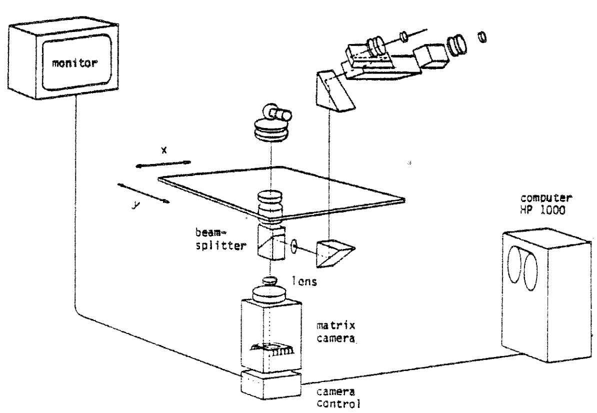

Fig. 1: Hardware configuration Planicomp C 100 with Hamamatsu video camera

The image area is projected through an optical system onto the sensor using a fraction of the light coming from the ordinary illumination system of the instrument. A beam splitter diverts 15 % of the light, which passes through the photograph, onto the video camera. An auxiliary optical system provides an enlargement of 1.35 from the image window onto the sensor array.

This arrangement has the advantage that the ordinary stereo observation by the operator is in no ways hindered by the digitization process. In fact, the operator does not notice the presence of the digitization system at all.

In the video camera signals are generated proportional with the intensity of the incoming light. Thus, the signals represent the density distribution of the image window in question.
The camera is a black-and-white video camera employing a solid state pickup device in the form of a MOS-type (metal oxide semiconductor) two-dimensional photo-sensor array developed by Hitachi,Ltd.
A summarizing sheet of specifications is given in table 1.

The device comprises a photodiode array and two scanners integrated on a p-type substrate. 320(H) * 244(V) photodiodes of which the unit cell size is 27μm * 27μm are arranged in an area of 8.8 mm * 6.6 mm . The scanners consist of horizontal and vertical shift registers positioned in the periphery of the chip. Scanning is done horizontally in the x-direction and repeated 244 times in the y-direction. In x-direction it is possible to choose starting point and number of scan lines. It is not the scope of this paper to delve into theory of charge coupled devices, it will therefore be referred to technical literature for extended information.

The output of the camera is an analog signal representing the array signals sequentially, column by column. It is converted into digital form by an A/D converter and delivered through an interface to the internal memory of the standard HP 1000 computer of the Planicomp. Some of the problems of scanning, data transfer and decoding, are described by A. Pertl (1984).

The program for high precision digital correlation was implemented on the standard HP 1000 computer of the Planicomp. The complete system is now operational with regard to automatic digitization of local image area and on-line computation of x- and y-parallaxes by digital image correlation.

Imaging device	:	MOS-type 2-dimensional photo sensor array
Number of pixels	:	320(H) * 244(V)
Scanning area		8.8 * 6.6 mm²
Scanning system	:	Progressive scanning
Resolution	:	Horizontal 240 lines (at center) Vertical 190 lines (at center)
Distortion	:	Less than ± 1 %
Signal-to-noise ratio	:	46 dB
Spectral response	:	400 nm - 1050 nm
Resolution range	:	256 steps (grey-levels)
Dimensions of camera body	:	62(W) * 48(H) * 131(L) mm
Weight of camera body	:	0.5 kg

Table 1: Specifications of Hamamatsu C-1035M video camera

This paper will present some problems and results of the first phase of investigations which concern the calibration and precision performance of the combined system. In particular the behaviour of the video camera system and some electronic and physical effects of the sensors on the precision of digital image correlation will be investigated. The paper will not deal, however, with other than hardware features which also influence the precision, such as all features related to the photographic image and to the method of image correlation.

After a review of possible error effects in chapter 1 experimental results of long term stability of the system are presented. Thereafter, in chapter 3, the internal precision performance of the system is investigated. For accurate geometric measurements the sensors must be related to the coordinate system of the Planicomp. In chapter 4 a calibration method is described.

Finally the results will be discussed and an outlook on future investigations will be given.

1. Hardware effects on the geometrical precision of digital image correlation

The hardware configuration is a hybrid system consisting of an analytical photogrammetric plotter and a CCD video camera system. If we want to study the behaviour of the combined system we should take both the photogrammetric and the electronic part of it into account. As photogrammetrist, however, we believe to have sufficient knowledge about the precision, systematic errors and the stability of the photogrammetric instrument. Therefore the following investigations are concerned mainly with the video camera system.

A number of error effects can easily be anticipated. There are first the components of the auxiliary optical system consisting of a beam splitter, lens for enlargement, lens of the video camera, glass-face-plate of the sensor array. Imperfection in manufacture and mounting will certainly influence the geometric fidelity of image digitization, although it may be expected that the effects will be constant in first approximation, including a possible error in the enlargement from the image to the sensor array.

Also the physical and electronic features of the system are subject to errors which may be partly constant or vary in time, especially as function of temperature variation. Constant effects of geometrical distortion may be due to:

- the physical arrangement of the picture elements in the sensor array. There may be deviation from a plane surface or deviation from nominal grating in terms of scale, affinity, gaps between sensor elements
- "Interior Orientation" of the CCD cameras, mainly consisting of decentering or inclination of the sensor plate against the optical axis.

Other electronic features of the sensor are time dependent as function of variation of internal or external physical conditions. As a result the precision and the long term geometric and radiometric stability is affected. Here especially the stability of geometric positioning is of interest. We may distinguish:

- constant or time dependent distortion, i. e. the degree to which the representation of positional information in the electrical signal deviates from the ideal physical position
- genuine time effects, such as warm-up characteristics and long term drifting
- temperature drifting as function of ambient temperature and humidity.

The manufacturer specifies a distortion of less than 1% with regard to the picture height of an electrically generated grating fitted as closely as possible to a known optical pattern.

Analyzing the CCD system more closely, a great magnitude of features can be listed which would distort the results in various ways. Examples are:

- Scan positioning
  Scanning is done horizontally in the x-direction and repeated 244 times in the y-direction. In x-direction there are 1024 positions feasible to start scanning but only 320 pixels. With an unfavourable choice of starting point and length of stride of scanning a vertical scan line might be sampled several times or even be omitted.
- Fixed pattern noise, i. e. the random variation of the properties of particular pixels, caused by local deviation of dark current (the signal which flows when no illumination reaches the face plate).
- Interaction of adjacent pixels, for example in the case of great differences in illumination.
- Blooming, i. e. when light of much stronger than the rating enters the solid state imaging device the charge overflows. This might happen at very bright signals on dark background.
- Shading, i. e. the variation in amplitude of an electrical signal when the illumination is uniform (Specification 5%).
- Burn-in effects, i. e. when the same object is shot over a long period or when an extremely bright light is shot.
- Lag, i. e. the ratio of the signal generated during the third scan, after continous illumination to the face plate is interrupted, to the signal in the steady state ⇒ comet tail effect
- Errors in A/D-conversion, transmission and decoding.

A thorough investigation into the geometrical precision and stability of the system will consider 3 main aspects in first instance:

- internal calibration of the sensor array
- constant positioning errors
- drift errors

Hereafter results are presented concerning the drift behaviour of the video camera system and the geometrical precision of the combined system.

The internal consistency of the sensor array is less critical, for the time being. There is no evidence yet for disturbing inconsistencies. Also the constant positioning errors, which are in the order of 1 pixel size, are of little importance. They can always be accommodated by a simple calibration between measuring mark and CCD output and taken into account numerically by applying appropriate shift parameters.

2. Drift measurements

A number of tests were made in order to get information about possible time-drifting of the sensor systems. For those investigations the analytical plotter is kept in a fixed position. The center of each sensor is put approximately on the area to be digitized in left hand and right hand image respectively. As ideal objects we chose grid crosses on glass plates, thus avoiding obvious effects by temperature, humidity and illumination. One or two minutes after switching on the cameras the series of measurements was started. The two windows were digitized and the correlation algorithm determined the center point in the left hand and right hand image section with regard to the pixel coordinate system (see chapter 4).

The measurements were repeated 6 times a minute over a period of up to 24 hours. During that period the setting of the Planicomp measuring mark was not changed. The recording was maintained within 1 µm.

The Planicomp system is located in a room without direct sunlight and a maximum change of ambient temperature of about 2 - 5° C . This long term test can disclose time- and temperature-effects on the stability of both the Planicomp and the video camera system.

Tests were repeated with locking on different objects. They all gave approximately the same results. It is therefore sufficient to show here one example only (see fig. 2.1 - 2.4)

This particular test was continued over a period of 24 hours. (In the plots of fig. 2.1 - 2.4 only every 6th measurement is represented, i. e. about one measurement per minute.)
Fig. 2.1 shows the variation with time of the x-coordinate of the center of gravity in left hand image section. It can be seen that during the first two hours there is a considerable drift. The x-coordinate increases by about 30 µm. In the following six hours the values still increase further by about 5 µm. Beyond this maximum there is a slight linear decrease.

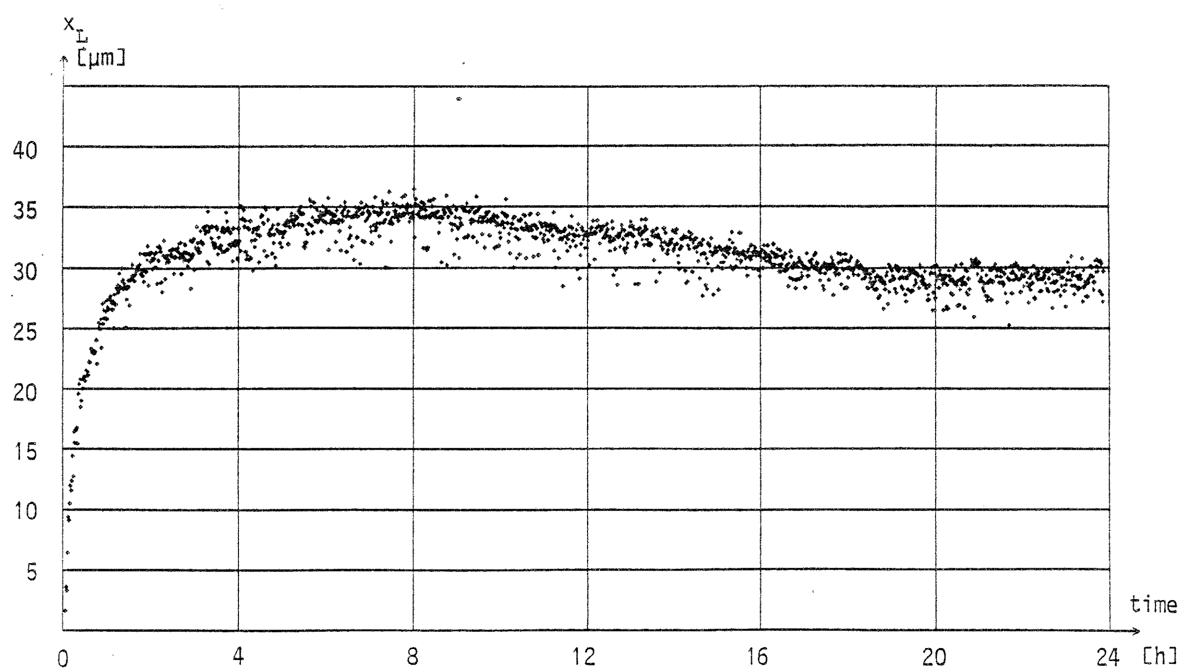

Fig. 2.1: Drift of x-coordinate (x_L), left sensor

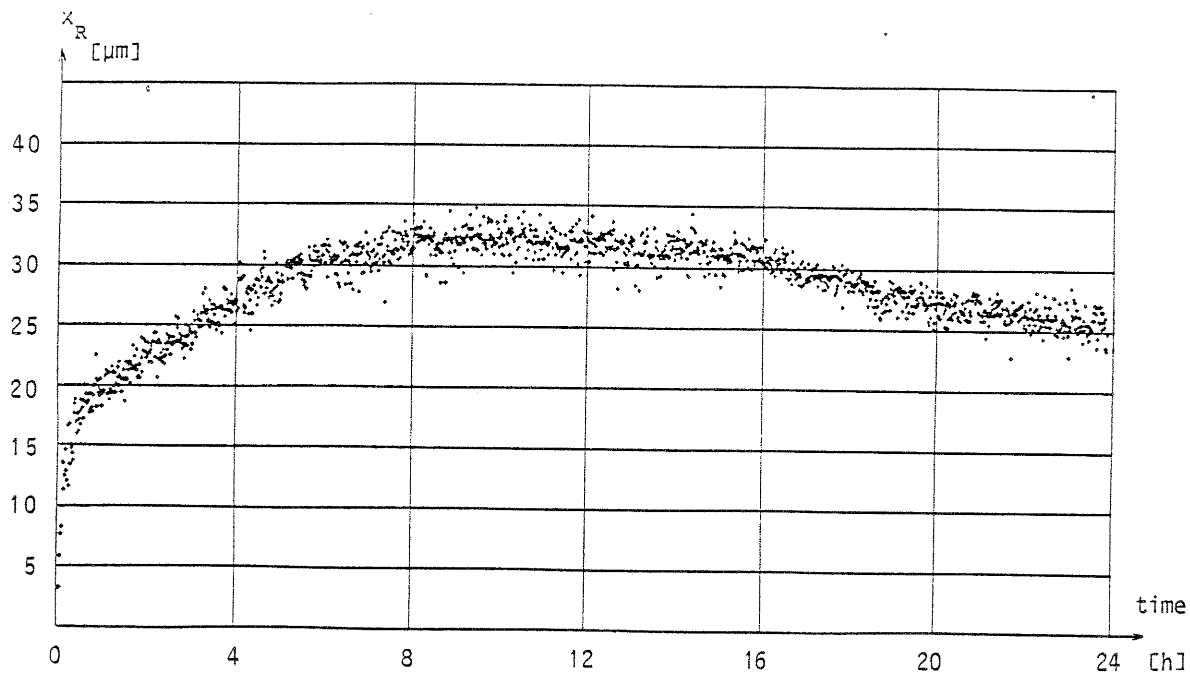

Fig. 2.2: Drift of x-coordinate(x_R), right sensor

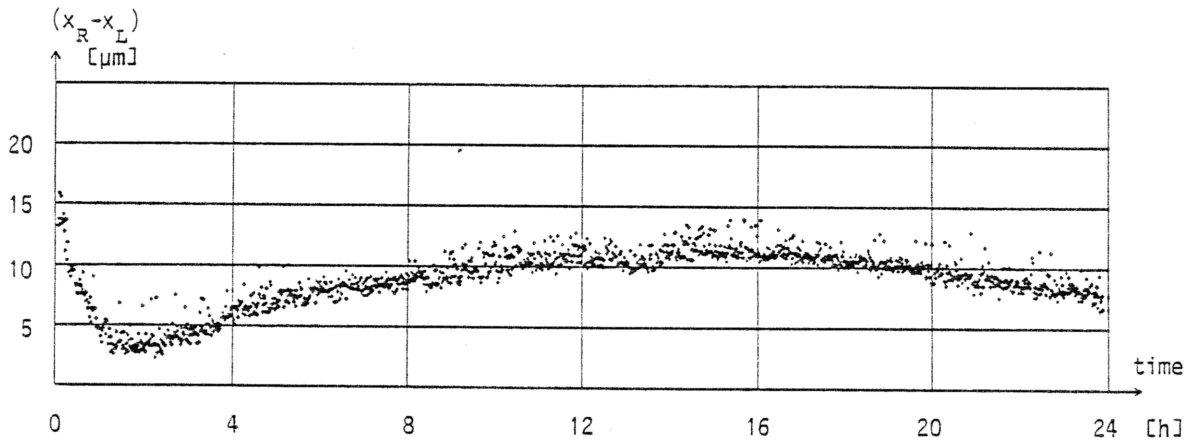

Fig. 2.3: Drift of x-parallax (x_R-x_L)

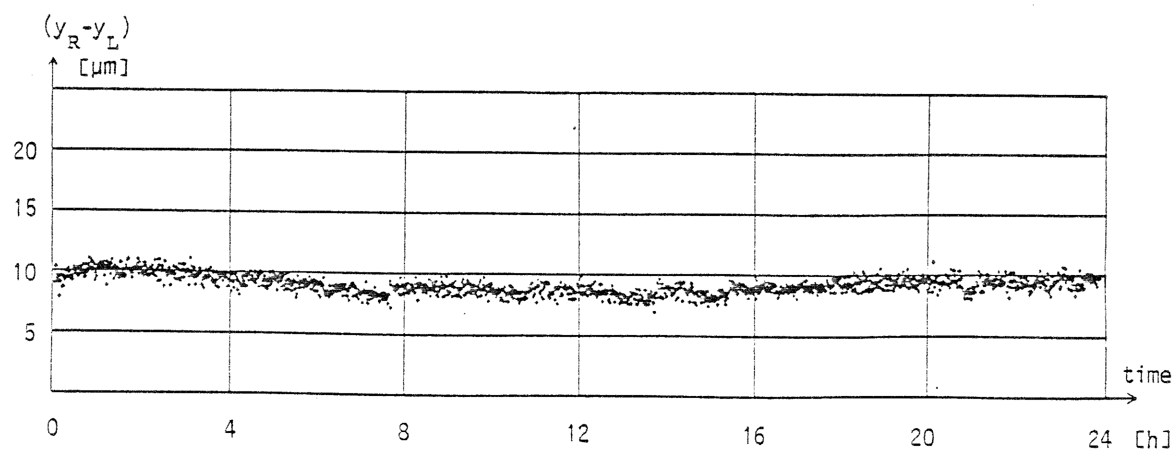

Fig. 2.4: Drift of y-parallax (y_R-y_L)

The time to approximately reach stability is about two hours, which is about four times as long as specified by the manufacturer. The characteristics of the sensor on the right hand side of the instrument differ considerably from the first one (see fig. 2.2). One hour after turn-on the drift of the x-coordinate reaches only 15 µm. Thereafter, over a long period of about 7 hours there is an additional linear drift of about 12 µm. Beyond that there is again a slight decrease. Thus, both sensors have an initial "warming up" period. After that there is slow drifting, but within periods up to 2 or more hours the drifting can be considered linear.

In many applications it is not the x-coordinates of each sensor but only the difference (parallax) between the two sensors which is of interest. Fig. 2.3 therefore shows accordingly the differences $(x_R - x_L)$ over the 24 h period. We can also see an initial drift of about 12 µm during the first two hours. The additional drift settles down to about 1 µm/hour and can again be considered linear within periods of up to several hours.

The drift behaviour of the sensors in y-direction is very much more stable than in x-direction. The position varies only by 1-2 µm over the whole period, for either sensor. In particular there is no marked warm-up effect. The individual results are not shown here. But fig. 2.4 displays that the drift behaviour of the y-parallax has the same favourable properties as just described for the y-coordinates individually.

From the drift investigations some conclusions can be drawn concerning precautions for high precision operations with the present system of CCD video cameras:

- The initial warm-up period of 1-2 hours should not be used for measurements.
- Thereafter the drift can be neglected for measuring periods of up to 1 hour.
- For longer measuring periods the drift may be recorded by reference measurements (on grid points or on fiducial marks for example) and be numerically taken into account.

When the above points are taken into consideration it is then possible to operate with the present video camera system and to rely upon an accuracy level of about 1 µm, without any further calibration or additional corrections. It is still another question whether we might be able to locate the causes of the drift in x-direction and perhaps reduce or compensate the effects. It is almost certain that the drift is caused mainly by temperature effects, and it may be of mechanical nature.

What happens if the cameras are frequently turned on and off has not yet been examined.
A number of other questions remain to be investigated; for instance the effects of great brightness variation on the sensors. At present, the illumination of the image still has to be adjusted by hand, separately for each point or area. (An automatic adaption of illumination is being prepared). However, such effects are to some extent covered by the investigation into precision and variation of precision as described in the following chapter.

3. System precision with regard to parallax determination by digital image correlation

The next series of investigations concerned the internal consistency of the system with regard to image correlation. A great number of observations were made, referring to different types of image points.

The measurements took place at least three hours after the cameras had been switched on and continued over a period of about 30 minutes, with 50 measurements per point. We used signalized points, grid plate crosses and also natural image points with good texture. Digitization and correlation was repeated 50 times at each point while the instrument setting was not altered. In this way the internal consistency or instability of the sensor system could be assessed empirically. The overall result is expressed in the range of empirical standard deviations for the shift values, as obtained by digital image correlation:

$$\sigma_x = 0.5 - 1.5\ \mu m$$

$$\sigma_y = 0.2 - 0.7\ \mu m$$

These internal precision values refer to pixel size 20 µm. They indicate only the internal stability of the system in a static position over time intervals of 30 minutes. In fig. 2.3 and fig. 2.4 one can also see that at present the results for x- and y-direction not only differ in drift characteristics of the system (see previous chapter) but also with regard to short term stability: $\sigma_x \approx 2 * \sigma_y$. The explanation for the differences between x- and y-direction are not yet clearly identified. It remains to be seen whether the effect can be removed.

The following series of tests embrace the consistency of the system with regard to the analytical instrument including the effects of different digitization on the image correlation.

Both sensors were approximately centered on homologous image points (e.g. grid plate crosses or signalized points). Then one sensor was kept fixed whilst the other was moved away in steps of 5 µm up to ± 2.5 pixels (50 µm) in either direction. The movements in x- and y-directions were first executed separatedly and thereafter combinedly. At each position the window area was digitized and the image correlation computed giving estimated shifts in x- and y-direction which were jointly compared with the coordinate readings of the Planicomp by similarity transformation.

Fig. 3.1 and fig. 3.2 show for one example the resulting differences v_x and v_y for the shift values in x- and y-direction. The object in this case is a natural point with a diameter of about 60 µm with good image texture.

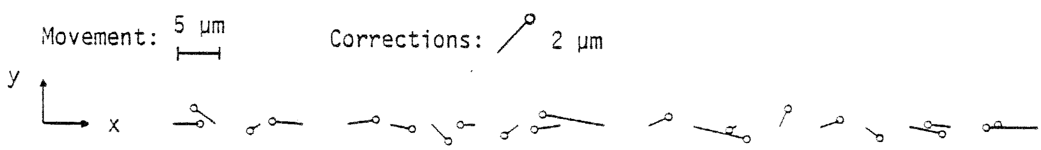

Fig. 3.1 : Corrections v_x, v_y - x-movement

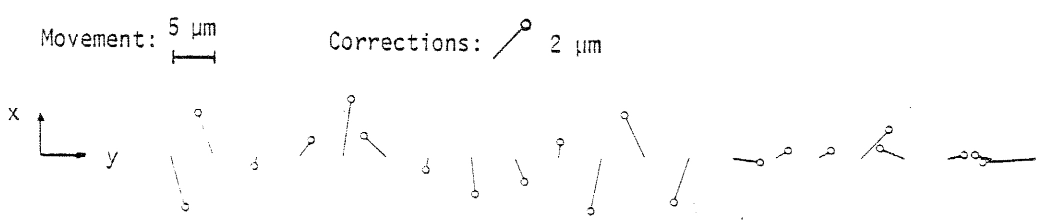

Fig. 3.2 : Corrections v_x, v_y - y-movement

The standard errors of the shift values from the digital image correlation (against the instrument reading) amount in this example to 1.0 µm in x- and 1.3 µm in y-direction. With a large number of experiments the standard errors were found to vary within a range of 0.8 - 2.5 µm. Those figures indicate the local and short term internal consistency and stability of the total hardware system with regard to digital image correlation.

4. Coordinate calibration

The sensor arrays constitute local coordinate systems for the digitization, realized in pixel units. For joint operations with the Planicomp both sensor systems must be calibrated internally and related to the machine coordinate systems of the respective plate carrier. The sensor array coordinate systems refer here to that part of the array which is selected by software addressing.

The calibration of the sensor system has two aspects. First the shift relations of the central point with regard to the machine coordinate system has to be established. Secondly the internal geometry of the sensor array has to be determined.

Both aspects can be jointly investigated, for each sensor array separately, by the following procedure:

The floating mark is set on an ideal object, like a grid plate cross, and the object is digitized. Digital correlation with regard to an artificial mask matrix of the object, positioned in the machine coordinate system as indicated by the measuring mark, would directly give the wanted shift relations between the sensor array and the machine coordinate system. If, in addition, the floating mark is shifted in regular intervals and each time the digitization and correlation is executed accordingly, then the geometry of the sensor array can be investigated at the same time.

This calibration can be refined to any wanted degree if special optical grating plates are used as target.
At present such calibrations are prepared. The preliminary results have already indicated that the internal geometry of the sensor array seems to be quite regular and that no greatly disturbing effects are to be expected. It seems that it is only the scale of the array system which needs calibration in first instance.

After calibration of the sensor array coordinate system the relation with the image coordinate system is established via conventional measurement or digital correlation onto the fiducial marks of the photograph. Then conventional measurements at the analytical plotter and digital image correlation can arbitrarily be interfaced.

5. Conclusions

In this paper the system performance of a Planicomp C 100 equipped with CCD video cameras for on-line digitization of local image areas has been investigated with regard to digital image correlation.

The investigations showed that the present hardware configuration shows some long term drift, apart from a considerable warm-up effect. The short term consistency and stability is, however, in the order of 1 - 2 µm. Thus, without further measures the system is capable of operating on this precision level. With additional calibration of the coordinate systems the system is ready for automatic coordinate and parallax measurement.

The precision of the hardware configuration seems sufficient for the time being, to apply the digital image correlation in practical photogrammetric operations. The great accuracy potential of the method, combined with sufficiently short operation times in the on-line mode open up optimistic prospects for successful and economic application.

At present further developments with regard to p rallax measurements (for relative orientation and digital terrain models), point transfer in a rial triangulation, and application to deformation measurement are being pursued.

Internally, detailed investigations will be cont ued which might be able to locate the causes of the drift characteristics of the system and o the observed differences in precision of parallax determination in x- and y-direction. Al o a more detailed geometric and radiometric calibration of the CCD sensor arrays has still t be done.

With such a refined calibration it is expected t at the high potential of the digital image correlation method can be further investigated and ex loited. The present system is already sufficiently accurate and versatile to continue the furthe development and experiments for direct photogrammetric application.

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