

Paper, presented at the 1984 Thompson Symposium, Birmingham, U.K.

DIGITAL IMAGE CORRELATION: PERFORMANCE AND POTENTIAL APPLICATION
IN PHOTOGRAMMETRY

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Abstract: A procedure for digital image correlation is described which is based on least squares window matching. The immediate aim is high precision parallax assessment, point transfer, and point measurement. Experiments and theory have confirmed the high accuracy potential of the method. By implementation of CCD video cameras in an analytical plotter Zeiss Planicomp C 100 an experimental hard- and software configuration has been established with which the operational on-line application of digital image correlation for conventional photogrammetric measuring tasks can be tested. First results of calibration and performance of the system are presented. They allow optimistic conclusions as to the further development and practical application of digital image processing in photogrammetry.

1. Introduction

1.1 This presentation is a progress report on some developments and investigations in the field of digital image correlation which have taken place at the Photogrammetric Institute of the University of Stuttgart during the past few years. The potential impact of image processing on the future development and status of photogrammetry will not be discussed directly. Nevertheless, by implication, the reported results touch strongly upon this theme of the 1984 Thompson Symposium.

1.2 Digital image processing has seen vast development, during the last decade, in many technical disciplines and especially in the field of remote sensing. However, those efforts were not primarily directed towards the standard photogrammetric measuring and mapping tasks which demand high geometric precision. Also image processing equipment was not interfaced with conventional photogrammetric instruments. Therefore most photogrammetrists, seemingly not directly concerned, watched the development from a distance. However, it became more and more evident that digital image processing has a great potential for high precision applications and that it will play a decisive part in the future development of photogrammetry.

1.3 In 1979, our institute seized the opportunity to join in the development of digital image correlation for high precision parallax determination and point transfer as part of a research program for remote sensing of the Deutsche Forschungsgemeinschaft. The general development in image processing has somehow not given special attention to this limited problem. Therefore it seemed appropriate to offer access to the field and to reach some practical results.

At the outset, a number of decisions were taken concerning the strategy and the bounding conditions of the development: The immediate aim was high precision parallax determination and point measurement. Therefore the approach was restricted to digital image correlation of small local image areas only. The correlation algorithm was to handle 2-dimensional arrays directly, without explicit reference to epipolar rays. The question of how to obtain initial approximate overlap of homologous image windows was, in the beginning, not to be treated comprehensively as its solution depends very much on operational circumstances.

Based on such general guidelines a correlation algorithm was developed, programmed, and tested. The operation was off-line, the digital input data coming from a Joyce-Loebl microdensitometer. The results turned out to be surprisingly accurate and direct application to photogrammetry became feasible. Consequently a hardware configuration was set up in which digital image correlation was integrated with an analytical photogrammetric plotter to provide on-line operation

and application to standard photogrammetric measuring tasks. In the following the main steps and some results of the development are reviewed.

Acknowledgement: The development was carried, and contributed to, at the beginning by R. Koller and E. Wild, in the later phase by A. Pertl, E. Gülch, and W. Förstner.

2. The special correlation algorithm

2.1 The digital image correlation procedure starts from digitised homologous image areas (windows) which overlap sufficiently and which are given in form of matrix arrays $G(x,y)$ of observed grey level values. The matrix elements relate to the respective pixel array, see fig. 1 and fig. 2. The computational task is then to obtain an optimum match by transforming one array of grey level values onto the other. Out of a number of possibilities, the most commonly used correlation function maximises the cross correlation coefficient of the two arrays by shifting one with regard to the other in a systematic trial and error procedure. We rejected this procedure on general grounds and adopted instead an approach in which the optimum match is defined by that transformation of one array onto the other which minimises the remaining grey value differences.

Any approach for high precision local image correlation has to take into account that the two homologous image areas to be matched differ both in geometry (different image, therefore in particular different relief displacement) and in radiometry (different photographs). It is the main property of our approach that such differences are rectified by applying geometric and radiometric transformation in the process of window matching and that the transformation parameters are obtained directly by an iterative least squares solution.

2.2 The special approach to digital correlation of local image areas is briefly explained for the one-dimensional case (fig. 3).

From the digitization process "observed" discrete gray value arrays $\bar{g}_1(x_i)$ and $\bar{g}_2(x_i)$ of the left and right hand windows, respectively, are given. They represent the quantised unknown image functions $g_1(x)$ and $g_2(x)$ which are perturbed by noise $n_1(x)$ and $n_2(x)$, respectively:

$$\bar{g}_1(x_i) = g_1(x_i) + n_1(x_i) \quad \text{and} \quad \bar{g}_2(x_i) = g_2(x_i) + n_2(x_i) \quad (1)$$

All functions relate to the same coordinate system, defined by the (identical) pixel arrays.

It is now assumed (mathematical model) that $g_2(x)$ is a transformation of $g_1(x)$, as both are images of the same object. Because of the small extension of the windows ($\approx 1 \text{ mm}^2$) it is sufficient, for the time being, to consider only linear geometric and radiometric transformations:

$$g_2(x) = h_0 + h_1 \cdot g_1(a_0 + a_1x) \quad (2)$$

The unknown transformation parameters represent a geometric shift and scale factor (a_0, a_1) and a zero-level shift and a brightness scale factor (h_0, h_1) of the grey level values.

Expanding (2) to linear increments from approximate values

$$\begin{aligned} (a_0 \ a_1 \ h_0 \ h_1)^0 &= (0 \ 1 \ 0 \ 1) \text{ or } g_2^0(x) = g_1(x) \text{ we obtain} \\ g_2(x) &= g_1(x) + \dot{g}_1(x)da_0 + x \dot{g}_1(x)da_1 + dh_0 + g_1(x)dh_1 \end{aligned} \quad (3)$$

where $\dot{g}_1(x) = dg_1(x)/dx$ is the gradient function of $g_1(x)$.

Considering now the difference

$$\overline{\Delta g}(x) = \overline{g_2}(x) - \overline{g_1}(x) = g_2(x) - g_1(x) + n_2(x) - n_1(x) \quad (4)$$

we obtain finally, when replacing $g_2(x)$ by the expansion (3), substituting $n_1(x) - n_2(x) = v(x)$, and switching back to discrete coordinates x_i :

$$\overline{\Delta g}(x_i) + v(x_i) = \dot{g}_1(x_i)da_0 + x_i\dot{g}_1(x_i)da_1 + dh_0 + g_1(x_i)dh_1 \quad (5)$$

Equation (5) represents for each pixel element i a linearized observation equation which relates the observed grey value differences $\overline{\Delta g}(x_i)$ with the unknown transformation parameters a_0, a_1, h_0, h_1 . The straight forward least squares solution minimises the (square sum of the) residual differences $v(x_i)$, thus representing the wanted optimum transformation, which gives the optimum window matching. The least squares solution does not present any particular problems. It has to be iterated, however, which implies resampling (see below). Also, the coefficients of (5) contain the unknown image function $g_1(x_i)$ and its gradient function $\dot{g}_1(x_i)$. Being not directly available they have to be estimated from the observed function $\overline{g_1}(x_i)$ by applying suitable smoothing procedures for filtering the noise $n_1(x_i)$.

Remark: The above derivation could be modified (Pertl 1984) by including the noise in the transformation (2). The formal result would be identical with (4), with a slightly different interpretation of $v(x_i)$.

2.3 The correlation algorithm which is actually applied is a two-dimensional generalisation of the case just described. It implies, in particular, a two-dimensional geometric transformation which is to rectify perspective distortion and relief displacement. In view of the small size of the image areas it is sufficient to apply affine linear transformation (six parameters $a_0, a_1, a_2, b_0, b_1, b_2$). Extension to more general transformation is feasible if required. The radiometric transformation remains restricted to the 2 parameters h_0 and h_1 as already described.

Working out the approach along the same line as in paragraph 2.2 we obtain, for each pair of homologous pixels ij of the two-dimensional arrays (i,j) , the following observation equation, which is the two-dimensional equivalent of (5):

$$\begin{aligned} \overline{\Delta g}(x_i y_j) + v(x_i y_j) &= \dot{g}_x(x_i y_j)da_0 + x_i\dot{g}_x(x_i y_j)da_1 + y_j\dot{g}_x(x_i y_j)da_2 \\ &+ \dot{g}_y(x_i y_j)db_0 + x_i\dot{g}_y(x_i y_j)db_1 + y_j\dot{g}_y(x_i y_j)db_2 \\ &+ dh_0 + g_1(x_i y_j)dh_1 \end{aligned} \quad (6)$$

This equation relates, pixelwise, the "observed" differences $\overline{\Delta g}(x_i y_j)$ of grey values with the unknown increments of the eight transformation parameters. In the coefficients of (6) the discrete values of the gradient functions $\dot{g}_x = \partial g_1(xy)/\partial x$ and $\dot{g}_y = \partial g_1(xy)/\partial y$ appear. As well as the coefficient of dh_1 , they have to be estimated by filtering the observed function $\overline{g_1}(x_i y_j)$. Evidently, the solution depends very much on the gradients which represent image texture.

The system is highly redundant, even with arrays of only 16×16 pixels. As equation (6) is linearized, the solution has to be iterated. This particular approach to image correlation offers the well known quality criteria of a least squares solution. In particular, a very good estimate of $\hat{\sigma}_0$ is obtained from the residuals v , indicating the goodness of match between the correlated arrays. It's magnitude is determined by the noise (difference) of both grey value arrays and by any deviations which are not mathematically modelled by the applied transformation. Furthermore, the weight coefficient matrix of the transformation parameters is obtained by inverting the 8×8 normal equation matrix. Although it is valid only within the mathematical model of the

algorithm, in connection with $\hat{\sigma}_0$ highly realistic estimates of the standard errors of parallax or point transfer are derived by propagation of error. Thus for each correlation, precision indicators are calculated. In addition, the resulting cross-correlation coefficient ρ between the two arrays is an estimator for the signal to noise ratio (SNR) in the respective image area:

$$(\text{SNR})^2 = \rho / (1 - \rho) \quad (7)$$

The correlation algorithm actually matches homologous image areas. As it is necessary to relate the resulting parallax or point transfer to a particular point, the weighted mean of the left hand array (with the squares of the gradients as weights) is chosen to represent the left image area:

$$\begin{aligned} x_s &= \sum_{ij} x_{ij} (\dot{g}_x(x_i y_j))^2 / \sum_{ij} (\dot{g}_x(x_i y_j))^2 \\ y_s &= \sum_{ij} y_{ij} (\dot{g}_y(x_i y_j))^2 / \sum_{ij} (\dot{g}_y(x_i y_j))^2 \end{aligned} \quad (8)$$

The corresponding point in the right hand array is identified by the geometric transformation parameters. Thus parallaxes and point transfer are clearly defined and their standard errors can be calculated.

2.4 The described least squares algorithm of the two-dimensional image correlation operates with linearized relations. Therefore the problems of approximate values, iterations, and convergence arise. Their operational aspects will be briefly considered in chapter 3.

A particular problem to be dealt with is known as resampling. Both windows are compared pixel by pixel, related by identical pixel number or pixel coordinates. After a transformation, this relationship is destroyed. Therefore, after each iteration step, the grey level values have to be interpolated onto the transformed coordinate system. This resampling was quite elaborate in the first program version. It has now been reduced to bilinear interpolation from four surrounding pixels. Nevertheless, it still takes a considerable proportion of the total computing time.

The image correlation algorithm which has been described above is non-symmetrical. All coefficients in equations (5) and (6) refer to the left hand window. This means that correlation of the right hand to the left hand window is not exactly identical with correlation in the reverse direction. A symmetrical procedure is easily established by averaging the coefficients from both windows.

3. First off-line experiments

3.1 During the first phase of the development, in which microdensitometer data were processed off-line, extensive experimentation took place, interfaced with theoretical studies (Ackermann, 1983). In the beginning windows of 64 x 64 pixels were used, with 50 μm und 20 μm linear pixel size.

It was found that the required initial overlap of homologous windows was about 75 % linear or > 50 % in area (with a linear pull-in range of 1/4 window size). Convergence of iterations was considerably speeded up by initial low pass filtering, which was abandoned in the last iteration steps. Low frequencies carry the convergence and high frequencies determine the final precision of correlation. In the latest program version, low pass filtering has been abandoned in favour of initial phase correlation (see Pearson et al., 1977) which operates with Fourier transforms and is robust in face of poor initial approximation. It has brought down the required number of iterations from about ten to three or four.

The geometric transformation was originally programmed as a four parameter similarity transformation. It is now replaced by the affine transformation which is quite sufficient for the present conditions of operation, in particular with regard to the now reduced window size of 32 x 32 or 16 x 16 pixels. Also 20 μm x 20 μm pixel size was found to be adequate with regard to the photographic resolution of standard aerial photographs.

3.2 The overriding and somewhat unexpected result of the first experiments was the very high precision of which parallax determination by digital image correlation is capable. The standard errors of x- and y-parallax, when operating with 64 x 64 pixel window size and 20 μm x 20 μm pixel size, came as low as 0.5 μm or even less, which is 0.05 linear pixel size. Although this figure refers only to internal precision, the result was surprising to all experts in the field. We found out later that such subpixel precision had been predicted previously and also that our gradient method of approach had been suggested before (Förstner, 1984). It is almost impossible to check such high parallax precision independently as it is beyond the limits of human stereoscopic perception. However, the closing errors of successive image correlation in loops confirmed the high level of precision.

This high precision of image correlation refers to well textured areas of standard aerial photographs. Poor image texture and smaller pixel arrays would affect the precision. It was also found that the precision of correlation between different channels of multispectral images deteriorates somewhat and is obtained only after some preprocessing for edge enhancement. The further considerations are therefore restricted to conventional air survey photographs.

3.3 The experimental investigations were accompanied and supported by parallel theoretical studies (Förstner, 1982; 1984). This is not the place to elaborate on the theory of digital image correlation. It was confirmed, however, that the precision of parallax depends mainly on the signal to noise ratio (SNR) and on the image texture, expressed in the variance of gradients. Furthermore, the results are influenced by pixel size, window size and preprocessing or filtering. An optimum pixel size exists which depends on image texture. It is around 20 - 30 μm in standard aerial photographs. An optimum precision of image correlation can be predicted which is related to the optimum pixel size. It depends on the gradient function, on the signal to noise ratio and on window size. With aerial photographs, the parallax precision can reach values $< 1\%$ of pixel size or $< 0.2\ \mu\text{m}$. On the other hand can the standard errors be very much larger in case of poor, low contrast image texture, a result which was also confirmed experimentally (Wrobel and Ehlers, 1980).

In general, the theory confirms the experimental results and makes the conditions understood under which these results can be obtained. In particular, the high precision level of which digital image correlation is capable has been confirmed.

4. Hardware implementation for operational on-line digital image correlation

4.1 The first phase of the development established the high performance potential of digital image correlation. Thus it became desirable to discard the time consuming microdensitometer digitising and off-line processing and to make the method operational for practical photogrammetric application in connection with stereoscopic restitution instruments. This implied hardware implementation of digitising equipment on an analytical plotter and reprogramming and interfacing of the method for on-line processing. With the assistance of the Carl Zeiss Company, Oberkochen, our analytical plotter Planicomp C100 was equipped, in the summer of 1983, with 2

Hamamatsu C1000/35M solid state video cameras which were selected particularly for their reputedly high geometrical stability (which nevertheless caused some problems later). Each video camera has a sensor array of 244 x 320 MOS (metal oxide semiconductor) elements of 27 μm x 27 μm pixel size and 256 (8 bits) intensity steps.

With the standard illumination system of the Planicomp, an image area is projected through an auxiliary optical system with x 1.35 enlargement onto the sensor array.

Thus the effective pixel size in the image plane is 20 μm x 20 μm , and the effective total window size is 4.9 mm x 6.4 mm. The video camera outputs a sequential analog signal of the scanned array. It goes through an A/D converter and an interface to be decoded and delivered digitally to the internal memory of the standard HP 1000 16 bit minicomputer of the analytical plotter. More technical details are given in Pertl (1984) and Gülch (1984).

15 % of the projected light is diverted onto the video camera and 85 % goes to the measuring mark and through the optical path of the instrument into the eyepiece as before. In this way the stereoscopic observation or measurement by the operator in the ordinary use of the instrument is not hampered at all. In fact, the operator does not directly notice that the central part of his field of view is being digitised.

This hardware configuration allows the integration of digital image correlation with the conventional measuring and mapping operations of the instrument. It also enables the operator to monitor the image correlation in two ways: He provides sufficient initial approximation and controls whether the local image area is suited for correlation. He also decides on the acceptance of the correlation on the basis of the quality parameters presented to him.

4.2 In parallel with carrying out these modifications to the analytical plotter, a complete reprogramming took place in order to reduce the computing time which was originally 80 sec per iteration on the Harris H 100 24-bit minicomputer. The system is now also implemented on the standard HP 1000 minicomputer of the Planicomp and interfaced with it for on-line operation. The procedure now starts with phase correlation requiring an initial linear overlap of 3/4 of the effective array size. It then proceeds to the iterative least squares solution, including resampling. Normally three or four iteration steps are sufficient. At present the effective array size is restricted to 16 x 16 pixels. Such arrays are accurate enough for photogrammetric application and allow, for the time being, completion of one correlation in 3 - 4 sec (digitising < 0.02 sec; signal transfer, conversion and decoding 0.5 sec; phase correlation 0.5 sec; least squares solution 0.5 sec per iteration). This is certainly not fast enough for all aspects of an operational system, especially as the effective array size will be increased again to 32 x 32 pixels. Nevertheless, it is sufficient for carrying on with experiments and testing.

4.3 After completion of the hardware and software implementation, the system had to be tested and calibrated. The tests still continue, concentrating on the following points (Gülch, 1984): (1) Zero-position of the arrays. The relationship between the digital arrays and the measuring marks with respect to the instrument coordinate system is established by measuring, digitising and correlating ideal objects such as intersections of grid lines.

(2) Drift behaviour. As anticipated the system turned out to be not completely stable. Having set floating marks and arrays on grid line intersections and leaving them untouched, automatic digitising and correlation every 10 sec over 24 hours showed the drift behaviour of the system, with regard to zero-position of the arrays and the resulting x- and y- parallax.

As Gülch (1984) has shown, the digital arrays have a considerable drift of up to 30 μm in

x-direction during a warm up period of 1 to 2 hours after switching on. Thereafter some slow long range drifting remains, at a rate of about 1 μm per hour, which can be considered linear within periods of 3 or 4 hours. The drifting happens only in the x-direction whilst the system is stable in the y-direction to within 1 - 2 μm . After the warm up period, precise measurements are possible within periods of at least 2 hours duration.

(3) Internal consistency of correlation. The repeatability of digital image correlation, when the instrument remains static, has been extensively tested, with series of 30 min each and 50 measurements per point. Standard errors of about 1.0 μm for x-parallax and of about 0.5 μm for y-parallax have been consistently obtained with grid line intersections (confirming the internal results of the drift measurements), with signalised points and with topographic features. Again, the dispersion in the y-direction is smaller than in the x-direction.

(4) The consistency of the total system, including the analytical plotter, was tested by holding the left hand array fixed and moving the right hand array in steps of 5 μm in either direction. The comparison of a large number of parallaxes obtained from digital image correlation with the preset increments gave standard errors for x- and y-parallax ranging from 0.8 - 2.5 μm .

Whilst the results of consistency and performance tests are not yet fully understood, it has been clearly established that the system is capable of parallax measurement by digital image correlation with an internal precision (standard errors) in the order of 1 - 2 μm . It has also been established that the system is operational and ready for application tests on that level of precision.

5. Practical application and performance tests; Outlook

5.1 For direct application in photogrammetry digital correlation must, as a start, be capable of the two elementary operations of parallax determination and measurement of image points, in particular of signalised points and of fiducial marks.

The special correlation algorithm as described in chapter 2 performs area correlation. It is directly suited to the measurement of x- and y-parallaxes. On the other hand, the definition (8) of a point makes the algorithm also directly suited, with some precaution, to the measurement of points. Although this capability must still be secured and refined the present system is applicable to measurement of points, or more general, of symmetrical geometric targets. This includes also grid line intersections for instance. As it is possible to correlate one array with an artificial image (of a reseau cross, a fiducial mark, or a signalised point) the algorithm can also be used for mono-measurements, as they occur in instrument calibration with grid plates or for interior orientation.

Before proceeding to practical application, extensive performance tests with real photographs were carried out and these are still in progress. Abundant material is already available but this can only be summarised briefly. Up to now most tests have been carried out with 1:8000 scale photography:

(1) Parallaxes, natural features. Series of measurements have confirmed that image correlation at quite arbitrary image areas with sufficient image texture gives results of consistently high precision. Generally speaking, the standard errors amount to 1 - 2 μm . With good image texture, whole series were obtained with standard errors < 1 μm . These standard errors are obtained as described in section 2.3. They indicate internal precision only and are not totally empirical. However, it can be estimated that the external accuracy remains within a

factor 2 of the internal precision figures. It must also be understood that the total image coordinate errors are composed of image deformation and the instrumental errors of the Planicomp system, in addition to the image correlation errors which correspond only to the errors of conventional stereoscopic setting of the measuring marks.

The σ_0 values are very often as low as 5 - 10 grey value steps out of the total range of 256. Accordingly the correlation coefficients have values above 0.90 and often above 0.95. This implies (see equation (7)), that the signal to noise ratio (SNR) in those selected image areas is very good, with values > 5 or even > 10 .

(2) Signalised points. The measurement of signalised points (see fig. 4) by digital image correlation achieves the same precision as the correlation of topographic features, with standard coordinate errors generally in the range of 1 - 2 μm and very often consistently $< 1 \mu\text{m}$. σ_0 values often are < 5 and $\text{SNR} > 5$.

(3) Fiducial marks. A special case of correlating signalised points is the matching of circular or other fiducial marks. In this case the observed matrix is correlated with a given artificial master matrix. The results are comparable with those for signalised points.

5.2 With the capability of measuring parallaxes and coordinates of points, the system can proceed to practical application tests. A prerequisite is, however, that the digital components are sufficiently calibrated and related to the coordinate system of the Planicomp, in order to allow interfacing of manual and automatic procedures. Also, the software output has to be interfaced with the data processing of the Planicomp. This has been achieved for some elementary operations, namely orientation based on digital fiducial mark measurements, and relative orientation, based on digital y-parallax assessment. With regard to relative orientation a first comparison can be given.

In a pair of wide angle photographs (1:7900 photo scale) 27 signalised points and 12 natural points were measured conventionally for (separate) analytical relative orientation. The same points were measured by digital image correlation. The internal standard measuring errors in the latter case were $< 1 \mu\text{m}$ (< 0.05 pixel size) for signalised points and $< 1.4 \mu\text{m}$ (< 0.07 pixel size) for natural points. From the various analytical relative orientations the σ_0 -estimates ($\hat{\sigma}_0^2 = \sum vv/n-5$) of table 1 were obtained, which also include image deformation and instrumental errors:

	signalised points	natural points
operator	3.1 μm	4.3 μm
digital coorelation	3.7 μm	3.8 μm

Table 1. Analytical relative orientation, σ_0 estimates

These results confirm, at least, that with the present hardware configuration, the digital image correlation performs as well as a high quality operator.

Beyond relative orientation, the system is capable of measuring digital terrain models (monitored by the operator, for the time being).

It also is capable of measuring signalised points for absolute orientation or for cadastral surveys. Investigations into such applications are being prepared.

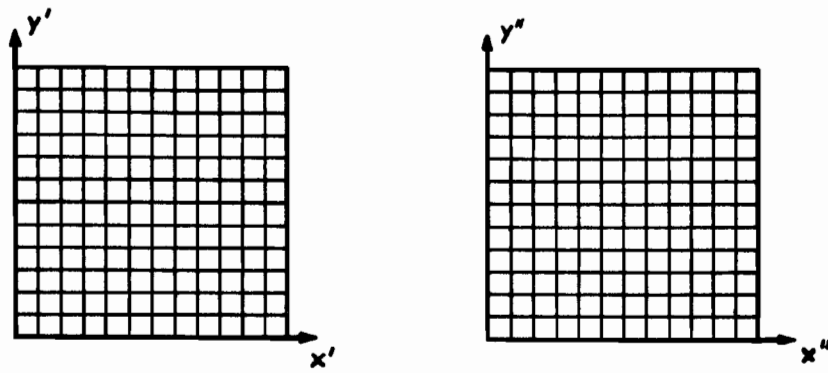
On the present level of performance, a special application becomes feasible which might be of great interest. It is the measurement of tectonic or other deformation. Digital image correlation is particularly suited for this special problem when applied to point transfer in photographs of different epochs. Tests are now in preparation which will investigate this particular application of digital image correlation.

Finally, digital image correlation can provide an almost ideal solution to the problem of point transfer for aerial triangulation. Here, the decisive property is that matrix arrays of unmarked tie points can be stored and re-used for point transfer without re-inserting the photographs in the instrument. In this case the operational advantages will be even more beneficial than the precision aspects. An operational system for digital point transfer will be developed next.

5.3 It is evident that, at the present level of performance of the combined system, already a number of standard photogrammetric measuring tasks can be solved by digital image correlation. We shall continue to complete the development of these applications. However, there are further extensions feasible. In particular, the extension of image correlation to feature matching will be of great interest. It will open the way to the semi-automatic recognition, location and mapping of topographic features. If we consider, in addition, the possibilities of line-following algorithms it can be foreseen that digital image correlation may considerably influence and modify a great part of conventional photogrammetric measuring and mapping procedures. Such extensions will require considerable hardware and software developments, and it is certain that difficulties will arise. Nevertheless, such developments become directly feasible and image processing may very well revolutionise photogrammetric instrumentation, working methods and performance sooner and to a greater extent than has been anticipated up to now.

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left hand window (1)
grey value matrix

right hand window (2)
grey value matrix

$$G_1 = G_1(x'_i, y'_j) = G_1(x_i, y_j)$$

$$G_2 = G_2(x''_i, y''_j) = G_2(x_i, y_j)$$

Fig. 1: Digitisation of small image areas

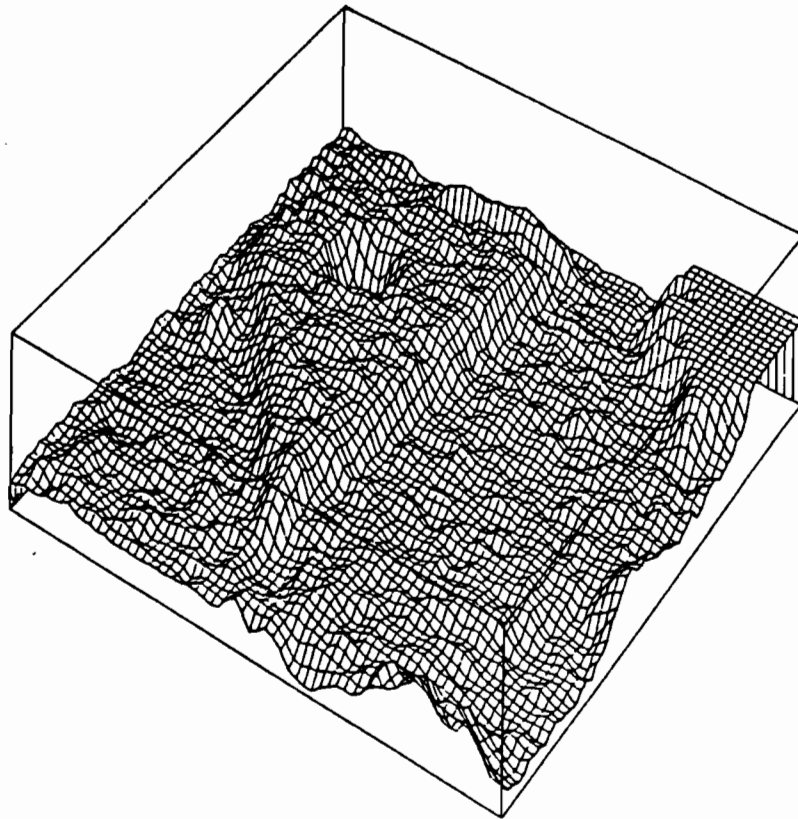


Fig. 2: Example of a digitised image of a road junction;
64x64 pixels grey value array

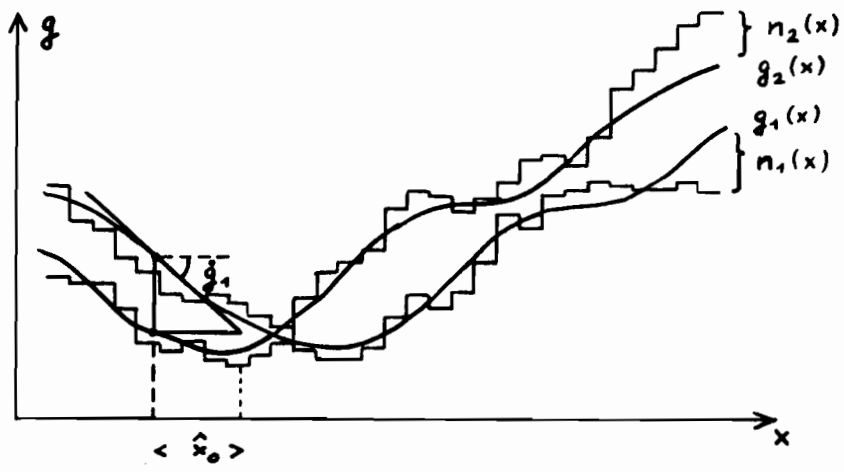


Fig. 3: Principle of the one-dimensional gradient method of window matching

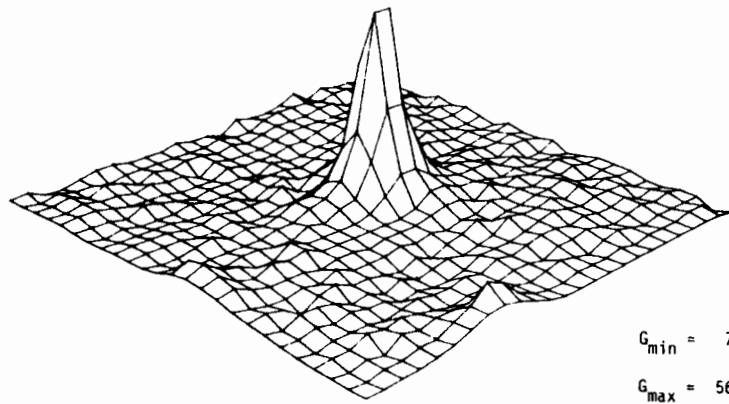


Fig. 4: Example of a signaled point

