DETERMINATION OF THE POSITION OF CROSSES WITH THE SUBPIXEL ACCURACY ON THE IMAGE TAKEN WITH THE CCD CAMERA.

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ABSTRACT: Digital images of 512x512 pixels, containing the record of a flat test of the 9 crosses of high contrast were registered using CCD camera model MTV 1081 CB. Centers of all crosses were computed using different digital evaluation methods. The coordinates of digital image compared with the object coordinates gave the standard error smaller then 0.1 of pixel. The description of experiment is given in the paper.

KEYWORDS: Camera CCD, Accuracy, Image Processing, Digital System, Close-range.

1. INTRODUCTION.

The nature of digital images stimulates the automatisation of interpretation and geometrisation. Specially automatic reading of images of targets occurs very promissing. There are already very good results of automatic derivations of coordinates published by Luhmann and Wester - Ebbinghaus [1986] or by Cruen & Beyer [1987] or by Streilein & Beyer [1991]. Being involved in the analytical plotters construction (this using the anologue continuous tone pictures and that using digital pictures displayed on the monitor screen [Jachimski & Zielinski 1992]), and having constructed the 6×6 cm reseau camera [Jachimski & Boroń 1992], it was quite obvious to begin the research connected with the computer supported reading of coordinates of targeted points from the digital images. To begin we have taken probably the easiest to solve problem - the automatic reading of coordinates of the reseau crosses from the analogue continuous tone pictures with the use of CCD camera and analytical plotter.

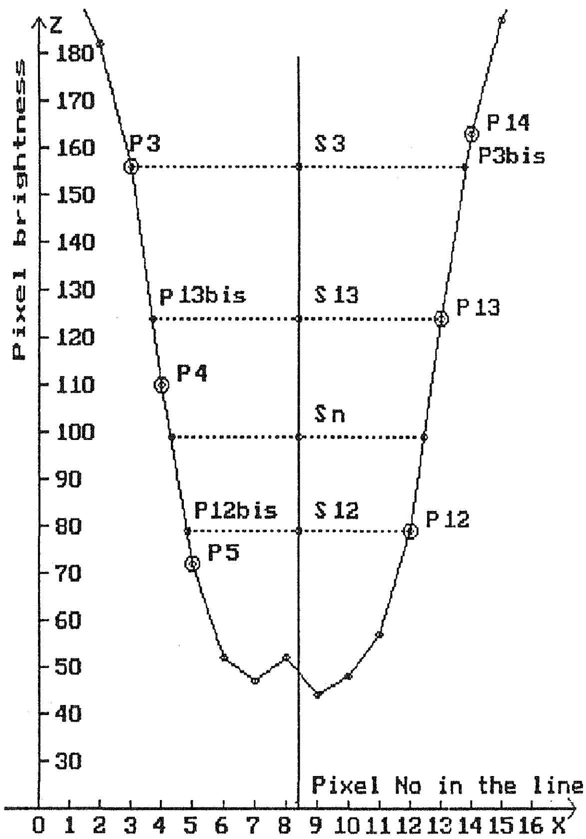
The result of the first step of corresponding research are presented below. The flat high contrast test of 9 thick crosses was recorded with the use of ordinary CCD camera. Various approaches to automatic interpretation and measurement of the position of the images of target-crosses gave quite promising results of subpixel accuracy better than 0.1 pixel.

2. THE DIGITAL CCD IMAGE OF THE TEST.

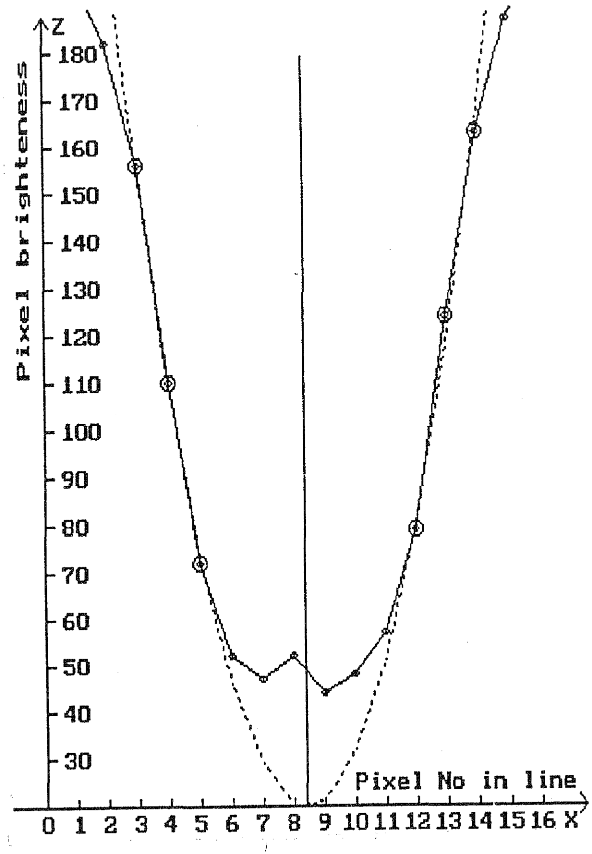
The digital image recorded with the use of CCD - Mintron MTV - 1801 C camera is composed of 512 lines comprising 512 pixels each. The elements of image matrix are written to the computer memory as a monodimensional vector of 512×512 = 262 144 elements. Each pixel uses one byte of memory to record the level of luminosity within the scale of 256 levels. The CCD image sensor of 6×4 mm size produces rectangular pixels 12×8 μm. The electronic circuit in the camera collects the image produced by the CCD sensors as a chain of electric charges, transform it to the analog TV signal and transfers it to the frame graber card in the slave computer. The frame graber card transforms that TV image again to the discrete form, and assigns one of the 0-255 numerical values to each electric charge proportionally to its intensity. During above transfers the errors of the camera and frame grabber clock synchronization can occur. This errors can produce same pixel lines shifts, resulting in assigning of wrong values of intensity to certain pixel positions. Therefore the digital images registered in the computer can slightly differ from the images produced by the CCD camera. The stability of images, which means the repeatability of recording of several subsequently one after another registered images of stable test can depend on warming-time of camera. The experiments have shown that relatively stable records can be expected not before two hours from the moment of camera work initiation (plug in).

To exercise the CCD image geometry a flat test of 9 crosses was produced. To the flat glass the 5 mm wide and 40 mm long nontransparent bars were glued to form 9 crosses. The crosses form 3×3 target test field of size 23×15 cm which fits well the 512×512 sensors portion of the CCD camera field of view. The test was measured using the Stecometer from Zeiss - Jena. The edges of each arm of each cross were measured in 6 section perpendicular to the arm axis. From the Stecometer readings the mathematical lines corresponding to the arms axes were calculated, and coordinates of the cross centers were found as the cross-section of the pertinent mathematical lines.

Several times in various moments the test was recorded using our CCD camera situated in the position approximately perpendicular to the test surface. The images were analyzed using various analysis algorithms, and the image coordinates of the centers of crosses were calculated. To compare



1a



1b

Fig.1 Examples of a section of the digital image brightness diagram produced by the computer. The section perpendicular to the arm of the image of a cross shows the profile line connecting individual pixels which:
a) serves as a basis for linear interpolation of the profile symmetry axis,
b) is approximated by the parabola, and a point on the axis of the cross is identified with the parabola axis

coordinates of centers of crosses on a digital image with original test the projective transformation fitting all 9 crosses of image and test according to the rules of the least square adjustment (tab.1) was applied. At the beginning two types of test images were analyzed : one taken with the objective Tevidon 1.9/35 mm from such distance that the test image was of the CCD 512×512 frame size, and second - which gave image 2.4 times smaller. Due to proper test lighting the images were very contrast: the background had the luminosity number around 210 while the black non-transparent crosses had only luminosity number 50. A contrast edge of the cross is imaged in each of the image scales with 3 pixels of relatively proportional increment of luminosity number. The diagram of luminosity of subsequent pixels along the image line or column (section of cross perpendicular to the arm axes) gives the polygon of the luminosity brightness distribution along the profile (fig.1). It is worth while to underline that the 3 pixel width of the transition stripe from the bright background to the dark cross surface does not depend on the image scale. It gives good opportunity to create an universal algorithm of the cross center determination on digital images.

3. PRECISE DETERMINATION OF CENTERS OF CROSSES ON A DIGITAL IMAGE.

There are several filters, which can be applied to determine image contours as a sharp lines (eg.- tresholding), but they do not offer the accuracy high enough to be used for precise determination of the cross center.

Therefore the more laborious methods based on the analysis of luminosity diagram along the digital image lines and columns were developed during 1991 - 92 period at our laboratories.

There are three methods which gave the accurate enough results to be considered as a solution to the problem :

- method of linear interpolation
- method of parabolic diagram approximation using minimalization of deviations of diagram points along :
  - lines
  - columns.

3.1 Linear interpolation along the luminosity profiles.

On the fig.1a there is a diagram of the the luminosity profile perpendicular to the cross arm axis with the pixels marked on it with circles. The profile is determined point by point only by pixels, their position along the line (or column) and by their brightness expressed in the 0-255 levels scale. The definition of the axis of symmetry for that profile would provide one point of the cross arm axis on the xz-image-plane. The simplest way to determine the luminosity profile symmetry axis it is to interpolate for each luminosity level of each existing pixel - the corresponding point on the opposite side of the diagram. For example, for the pixel marked by P3 would be interpolated linearly point $P3_{Bis}$ among pixels P13 and P14, and for pixel P13 would by linearly interpolated the corresponding $P13_{Bis}$ point among pixels P3 and P4. The center of symmetry S13 of the vector P13 - $P13_{Bis}$, center of symmetry S3 of the vector P3 - $P3_{Bis}$, and other centers S_i calculated that way can be used to calculate the final mean value of their position along the line (or column). This mean center position mean-X_S would identify the point on the axis of the cross arm.

To ensure better accuracy this method is modified as follows. The interpolation is performed not only for pixels, but additionally for each full value of brightness (eg. for 150, 149, 148 etc.). Symmetry center position S_i is calculated as a mean value of all x - value of the points which were found on certain luminosity level by the interpolation. The levels containing less or more than 2 interpolated points are neglected. After all symmetry centers were determinate, the mean value mean-X_S is calculated, and S_i canters which differ more than 1 pixel are selected and rejected. The next iteration of mean-X_S calculation is performed without points rejected during first iteration. The iteration process is repeated with the successive selection of center points differing from the mean value more than 0.1 pixel and 0.01 pixel. The mean-X_S value calculated for the S_i points which were not rejected in the third iteration is final. Final mean-X_S can be treated as the point of analyzed line on the digital image surface which can be considered for determination the axis of the analyzed arm of a cross.

After the iterations for certain line were accomplished we can analyse which pixels (luminosity levels) were not excluded during calculations. The pixels representative for certain luminosity diagram are those pixels which were accepted to determine vectors along which the interpolation for symmetry axis have been permitted.

3.2 Approximation of the luminosity profile using the parabola equation.

The parabola which approximates pixels along the luminosity profile can be determined by calculation coefficients a, b, c of the parabola equation for at least 3 points pixel of a profile. In case that the greater number of points determines the profile the correction equations of the type

$$V_z = ax^2 + bx + c - Z$$

can be solved applying the least squares method (fig.1.b). To get acceptable results the calculations should be based only on the pixels representative for the profile (see 3.1).

The calculation of the parabola coefficients with the use of analysis of V_z deviations is very easy for the schematization, because normal equations for it are:

$$\begin{cases} [x^4]\,a + [x^3]\,b + [x^2]\,c - [x^2 z] = 0 \\ [x^3]\,a + [x^2]\,b + [x\ ]\,c - [x\,z] = 0 \\ [x^2]\,a + [x\ ]\,b + \quad bc - [\,z\ ] = 0 \end{cases}$$

Considering that calculations are always performed for the predetermined image segment (eg. predetermined with the use of simple filtering; tresholding), one can assume a local coordinate system for each cross. In that local coordinate system the pixel numbers which identify representative pixels will be these same for many profiles (especially, when the size and shape of various cross images are these same). This gives possibility to use precalculated coefficients of the normal equation what speeds up very much the calculations.

The position of the axis of the symmetry profile can be determined from the first derivative of the parabola equation :

$$\frac{\partial z}{\partial x} = 2ax + b \quad \text{and} \quad x = -\frac{b}{2a}$$

The method of determination of a parabola by the minimalization of the V_z deviations is very simple, but seemed to be not optimal for the parabola with the symmetry axis parallel to the z-axis of the coordinate system. Therefore additionally the parabolic approximation with the use of V_x deviations minimalization was elaborated. The calculations here are more time consuming, because they call for iterations due to the indispensable correction equation linearisation. The V_x correction equation is :

$$V_x = \frac{\partial x}{\partial a} a + \frac{\partial x}{\partial b} b + \frac{\partial x}{\partial c} c \pm x_o - x$$

where :

$$x_o = \frac{-b \pm \sqrt{b^2 - 4a(c-z)}}{2a}$$

$$\frac{\partial x}{\partial a} = \frac{b\sqrt{b^2 - 4a(c-z)} \pm b^2 - 4a(c-z) \pm 2a(c-z)}{2a^2\sqrt{b^2 - 4a(c-z)}}$$

$$\frac{\partial x}{\partial b} = \frac{-\sqrt{b^2 - 4a(c-z)} \pm b}{2a\sqrt{b^2 - 4a(c-z)}}$$

$$\frac{\partial z}{\partial b} = \frac{\pm 1}{\sqrt{b^2 - 4a(c-z)}}$$

To solve the above equations there is necessary to predetermine the approximate values of the unknowns a, b, c, therefore the use of this method had to be preceded by the use of the ΣV^2_z = minimum method.

4. THE ACCURACY ANALYSIS AND CONCLUSIONS.

The two shots (long distance - image „2" and close - up - image „1") of 9 crosses test were analyzed applying 3 above described methods. Image „1" presented a single crosses 72.7 pixels wide and 108.1 pixel high, with the vertical arms 9.1 pixel thick and horizontal arms 13.5 pixel thick.

Image „2" presented a single cross 30.0 pixels wide and 44.9 pixels high, with the vertical arms only 3.8 pixel thick and horizontal arm 5.6 pixel thick.

Due to the high image contrast and clear background there were no problems during the analysis. Each arm of each cross was analyzed separately. Vertical arms were analyzed along the lines and horizontal arms along the columns of the digital images. Image „1" allowed for 100 sections of vertical arm and for 65 sections of horizontal arm, while image „2" allowed only for 35 vertical arm sections and for 25 horizontal arm sections.

The position of the axis of symmetry was derived for each section of luminosity profile and it was treated as a single point of the axis of symmetry of the cross arm on the surface of the CCD image. All that points issued using one of the 3 analysis methods were approximated by a straight line for horizontal arm of the cross and by another straight line for vertical arm of the cross. By the intersection of that two lines approximating arms of a cross the image coordinates of the cross center are fixed.

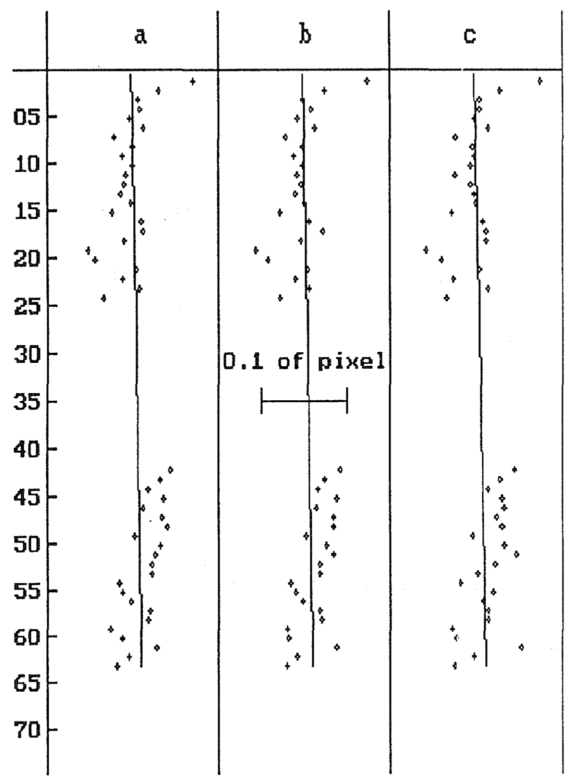


Fig.2. Linear approximation of the points determination on the digital image surface by subsequent parabolas axis. The diagram was produced by a computer program which automatically calculates points on the axis of the arms of a cross along all the digital image lines or columns.

On the fig. 2 there is an example presented of the approximation of arms of the cross nr.1. analyzed on the image „1", resulting from the 3 methods of digital image interpretation. The dots represent positions of the luminosity profile symmetry axes.

To value the accuracy of automatic determination of coordinates of crosses on the CCD image, an ideal image of the test was calculated. It was calculated by the projective transformation of the original flat test coordinates onto the CCD sensor surface under condition of the least square adjustment. In the adjustment procedure the deviations V_x and V_y were minimalysed simultaneously for all 9 crosses,separately for each image. The results of analysis of both images using 3 investigated methods are shown in the tab.1.

The deviations are not big, in spite of the fact that the corrections for objective distortion were not taken into account. The mean errors mx and my do not exceed 0.04 pixel, what is very promising.

Comparison of the mean errors resulting from each of 3 analyzed methods does not show big differences. In conclusion we can exclude the use of the most troublesome method of ΣV^2_x = min parabolic approximation, and consider for further use the method of linear interpolation or method of ΣV^2_z = min parabolic interpolation. The further practical exploitation of the selected methods will allow for the final valuation in which not only accuracy but also the reliability and time consumption must be considered as an important factors.

Tab.1.

Residual deviations after projective transformation of 9 points test coordinates onto the digital image coordinate system. ([μp = 0.001 of a pixel]).

	image„1”						image „2”					
	image „1” covers full CCD frame surface 1 pixel ≅ 0.55×0.37 mm						image „2” is in the scale 2.4 times smaller then image „1” 1 pixel ≅ 1.32×0.89 mm					
	A		B		C		A		B		C	
	V_x	V_y	V_x	V_y	V_x	V_y	V_x	V_y	V_x	V_y	V_x	V_y
	[μp]		[μp]		[μp]		[μp]		[μp]		[μp]	
1	0	19	2	27	4	30	12	11	-2	-3	21	-34
2	-24	-34	-11	-40	-13	-53	-6	-34	9	-1	-4	1
3	9	27	5	27	6	36	-17	30	-10	24	-19	27
4	8	5	1	13	1	16	-21	23	-27	21	-28	73
5	10	-66	-14	-75	-14	-81	-6	-30	11	1	-10	-6
6	11	36	18	35	19	38	49	-8	21	-64	43	-54
7	12	10	6	4	10	8	12	9	17	-20	4	-23
8	-26	31	5	28	-2	25	6	-23	5	2	20	-27
9	0	-29	-13	-18	-11	-20	-29	22	-24	38	-26	44
	m_x	m_y	m_x	my	m_x	my	m_x	my	m_x	my	m_x	my
	14.0	33.0	10.0	35.3	10.7	40.2	22.0	23.0	16.3	27.8	22.7	38.5

Note:

The A, B, C columns show the residual deviations of image coordinates achieved using various methods of the axis of the arms of cross automatic determination on the CCD digital image of the test:

- A - method of the linear interpolation along the luminosity profile
- B - method of the luminosity profile approximation by parabola under ΣV^2_y = min condition
- C - method of the luminosity profile approximation by parabola under ΣV^2_x = min condition.

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