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Precise and Reliable Image Shift Detection by a New Phase Difference Analysis Method

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Abstract

This paper describes a new approach for precise image shift detection between two images. The approach is based on an analysis of the phase difference spectrum between two images. Image shifts are directly evaluated from the phase difference spectrum without Fourier inversion. The cross spectrum is utilized as the weight parameter distribution. Synthetic and real images of typical image patterns were used in the experiment. Accuracy as high as 0.01 pixel, which has never been stably obtained with conventional methods such as phase-only correlation, is achieved stably and reliably for all of the image patterns.

1 Introduction

Precise and robust image shift detection is effective for object tracking, pattern inspection, machine vision calibration, and so on. Accuracy of the order of 0.01 pixel is especially required for fine alignment of object and image positions in LSI production.

The local pattern matching correlation has been widely used to detect image shifts.[1-4] In this method, the correlation function obtained when the input image is shifted in one-pixel increments by computer is approximated to a linear equation, e.g., the parabolic equation, by the least-squares technique. Then, the local minimum point where the equation is minimum is located. As the input data sampling resolution is one pixel, the accuracy obtained is usually a few tenths of a pixel and a tenth of a pixel at best, and it tends to be unstable. On the other hand, in the phase-only correlation (POC) method, after two images are Fourier transformed, only the phase difference distribution is inverse-Fourier-transformed.[5-8] The calculation is simple and accuracy as high as a few tenths of a pixel is easily obtained. The accuracy of a tenth of a pixel can sometimes be obtained. However, our detailed experiments have shown that the correlation distributions calculated by POC sometimes have multiple split and blunt hills, and detection errors tend to strongly depend on the image patterns and method of image acquisition. The experimental detection accuracy of POC will be mentioned later in this paper.

To cope with the problem, we have developed a new approach for image shift detection that takes cross amplitude distributions into account which have not been considered in the conventional methods.

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The approach is based on an analysis of the phase difference spectrum between two images.[9,10] Image shifts are directly evaluated from the phase difference spectrum without Fourier inversion. In course of the calculation, the cross spectrum is utilized as the weight parameter distribution.

Synthetic and real images of four typical image patterns were used in experiments. The image shift detection for synthetic images was carried out by moving reference images synthetically by computer. In the real-image experiments, printed images were moved by a mechanical stage. Accuracy as high as 0.01 pixel, which has never been obtained stably by conventional methods such as POC, was obtained stably and reliably for all of the image patterns. This new detection technique meets the severe requirement satisfactorily, paving the way for application of machine vision to sensitive object control and inspection.

2 Principle

The cross amplitude spectrum Cr and phase difference spectrum Ph are given by

$$Cr(u,v) = |F\{I_1(x,y)\}\ F\{I_2(x,y)\}| \quad (1)$$
$$Ph(u,v) = \arg\ [F\{I_1(x,y)\}\ F\{I_2(x,y)\}] \quad (2)$$

where $I_1(x,y)$ and $I_2(x,y)$ are the reference image and the input image, respectively. F denotes the Fourier transformation, and u and v are respectively lateral and vertical axes in the frequency domain. If the image shift direction is known beforehand, the image shift can be calculated from the phase difference for each frequency component. However, if the direction is unknown, the shift can not be directly calculated.

The lateral and vertical direction image shifts, dx and dy, respectively, for each frequency are related by

$$a\,dx+b\,dy=c \quad (3)$$

where constants a, b and c are dependent on the shift direction t, frequency f, and phase difference $\Delta\theta$. On the voting space with lateral and vertical axes dx and dy, respectively, votes at coordinates on the straight line given by eq. 3 for each frequency are incremented by one. In the case of ideal images without noise, all of the lines should intersect at a common point and the voting space should feature the delta-shape at the point. However, intersections spread out widely due to phase dispersion caused by noise and digital sampling in the image acquisition, so it is almost impossible to find the true intersection point even in computer simulation using synthetic images. The phase dispersion tends to be much larger for low-amplitude frequencies than for high-amplitude frequencies. To cope with the problem, the modified voting space is used for the above-mentioned voting space. On the space, the straight line given by eq. 3 for each frequency increments the numbers of votes at coordinates on the line by the number given by the weight function for the frequency._ Then, the probability density distribution (PDD) representing the voting concentration measure is calculated with the resolution of 0.01 pixel. The distribution PDD is given by

$$g(dx,dy) = \Sigma f(w,d) \qquad (4)$$

where w is the weight parameter set for determining the weight for each frequency from the cross spectrum and d is the distance from (dx,dy) to the line. The f is the weight function. By using the weight function, contributions of frequencies with small amplitudes to PDD, which sometimes cause fatal image shift detection errors, become considerably small. Then, the local maximum of PDD is found to evaluate image shifts.

The phase difference spectrum contains unknown offset $2n\pi$, where n is the integer dependent on the frequency. The un-lapping procedure is performed to calculate the offset for each frequency and the above-mentioned detection procedure is partly repeated again to finally determine the image shift.

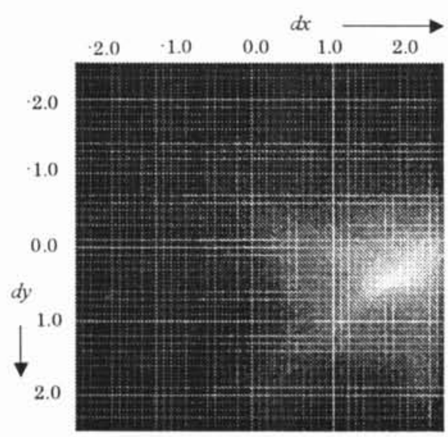


Fig. 1 The voting space

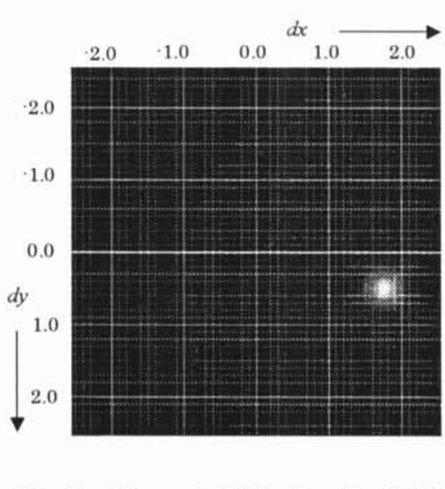


Fig. 2 The probability density distribution

Figure 1 is an example of the voting space where eq. 3 for all frequencies are plotted. The true lateral and vertical image shifts are 1.75 and 0.50 pixels, respectively. The shift (0,0) origin is set at the center of the figure. The thick lateral and vertical lattice lines show the 1-pixel spacing and the thin lattice lines show the 0.1-pixel spacing. The calculation resolution is 0.01 pixel, though it is not drawn in the figure. As shown in Fig. 1, it is clear that intersections spread out too widely to find the true intersection point. Figure 2 is the image shift probability density distribution PDD. The axes are the same as those in Fig. 1. Evidently, the distribution features a sharp cone shape. The local maximum is obtained in the resolution of 0.01 pixel directly without interpolation.

3 Experiments and Results

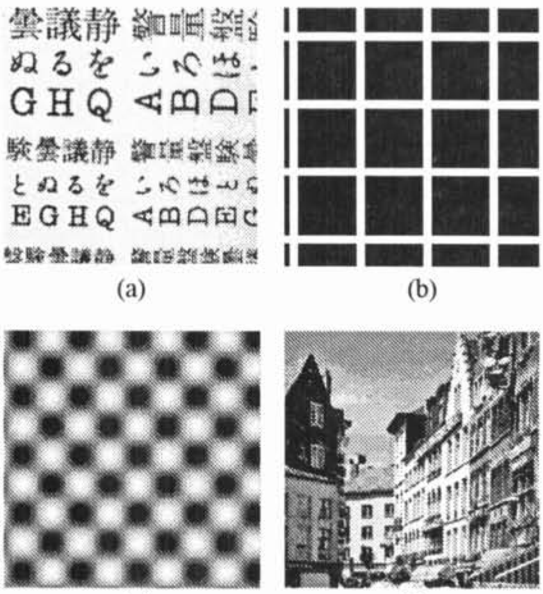
Figure 3 shows four sample image patterns used in the experiments. Pattern a is a character string image with binary gray levels, which contains various orientation edges. Pattern b is a lattice pattern image, which has strong edges at pattern component boundaries. Pattern c is a sinusoidal pattern image, which has no sharp edges. We call it the sponge pattern. Pattern d is a SCID scene image, which has many thick and thin segments, and large and small regions as well as many gray levels.

In the synthetic-image experiments, synthetic images of the above four patterns were generated as reference images and then input images were generated synthetically by shifting the images by linear interpolation. In the real-image experiments, the standard test-chart for pattern a, print-outs of computer synthetic images for patterns b and c, and a print-out of the SCID data for pattern d were mounted on a mechanical stage. After calibrating the relation between the stage movement and the amount of image shift, input images were acquired by the CCD camera as the stage was moved.

Figure 4 is the cross spectrum for pattern a. In Fig. 5, the phase difference spectrum is shown in 8-bit levels after adding 2π to the values of phase differences. The obscure straight band region with the half-tone level should be perpendicular to the image shift direction. However, the phase dispersion due to noise is too large to exactly determine the direction.

Figure 6 shows the error distribution in the phase difference spectrum. Figure 7 is the distribution of the distances from the true point to the lines given by eq. 3 on the voting space. Although errors in the phase difference are dominant in the high-frequency region, those in the distance are dominant at lower frequencies. Figures 8 and 9 are the error distributions obtained when the un-lapping procedure was carried out. It is clear that the errors are explicitly reduced by this procedure. However, non-negligible errors in the distance still exist sparsely at lower frequencies. Therefore, to achieve high accuracy and stability, as many phase difference data as possible have to be used in the calculation considering the cross spectrum.

Table 1 shows detected lateral and vertical image shift values. The true lateral and vertical shifts are 0.25 and 0.75 pixel, respectively. The resolution in the calculation was set to 0.01 pixel and the local maximum point in the probability density distribution was found without interpolation.



(a) (b) (c) (d)

Fig. 3 Image patterns used in the experiment.

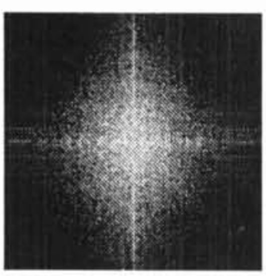


Fig.4 The cross spectrum.

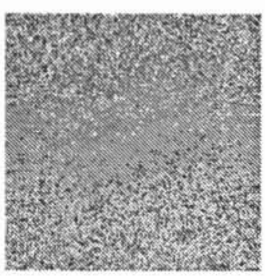


Fig.5 The phase difference spectrum.

Fig. 6 Errors in phase difference spectrum

Fig. 7 Errors in the voting function.

Fig. 8 Errors in phase difference spectrum

Fig. 9 Errors in the voting function.

For comparison, results of detection by means of the conventional POC method are also shown in the table. The resolution in the calculation was set to 0.01 pixel. In this method, the local maximum point in the correlation was obtained as the detected shift. When the correlation distribution has multiple hills or a dull irregularly shaped hill in it, local maximum points are far from true. In this case, the gravity center of the region containing the hills was calculated as the detected shift.

It is clear from Table 1 that our method is highly accurate and highly stable for all of the image patterns. The average error is 0.010 pixel and the standard deviation is 0.007 pixel at worst. In POC, on the other hand, detection accuracy largely depends on image patterns, and it is impossible to detect image shifts for pattern *c*, which has a single frequency.

Figure 10 shows the detection result obtained when the stage was moved laterally and vertically in 0.25-pixel increments. The image sample is pattern *a*. The true shifts are at the intersections of the lateral and vertical lines. Detected image shifts are shown by solid marks. The average detection error is 0.01 pixel, which corresponds to the resolution in the calculation. In the figure, the error tends to increase as the shift becomes large. This may be due to error in the calibration of the relation between the stage movement and the image shift and also due to the backlash of the mechanical stage. For comparison, the result for the POC method is shown in Fig. 11. When the correlation distribution splits off to form some hills, local maximum points are far from true, so the gravity center of the region containing the hills was calculated as the detected shift. As shown in the figure, errors of over a quarter pixel are observed and it is clear that detection error depends largely on the amount of image shift.

In summary, our proposed technique gives accuracy as high as 0.01 pixel, which has never been obtained stably by conventional methods such as POC, stably and reliably for all of the typical image patterns used in the experiment.

4 Discussions

The proposed method offers high accuracy and reliability for the real image of pattern *a*, while POC generates large errors for it. Let us consider the reason. Amplitudes at higher frequencies are relatively low due to CCD camera image acquisition properties. Because of the low amplitudes, phase differences at higher frequencies easily fall into disorder due to image noises. This results in low accuracy of detection for POC. On the other hand, in our proposed method, the weight function effectively reduces the contribution of low-amplitude frequencies to the calculation and resultantly high accuracy and reliability can be realized.

This explanation holds good for pattern *b* too, where low-amplitude frequencies exist widely even in low-frequency regions. There are even more low-amplitude frequencies in pattern *c*. Conventional POC is unsuitable for this kind of image patterns. The results for pattern *d* are explained as well.

The correlation distribution in POC sometimes contains multiple hills, depending on the amount of image shift. The half-pixel locking phenomenon was also observed in our experiments, though the reason is unclear yet. In contrast, in our method, the probability density distribution has a regular cone shape and it does not split even when the image is shifted at a wide range. This provides high stability in image shift detection.

The probability density distribution depends on the expression of the weight function. It is possible that optimization of the weight function could further improve detection accuracy and reliability. How to optimize them remains as future work.

5 Conclusion

This paper described a new phase difference analysis method for precise image shift detection between two images. Image shifts are directly evaluated from the phase difference spectrum without Fourier inversion. The cross spectrum is utilized as the weight parameter distribution. Synthetic and real images of typical image patterns were used in the experiment. Accuracy as high as 0.01 pixel was obtained stably and reliably for all of the image patterns. The approach is effective for fine alignment of object and image positions in fields such as LSI production. It paves the way for the development of object tracking, pattern inspection, machine vision calibration, and so on.

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Table 1 Detection results for the four image patterns.

Images		Proposed		POC	
		Lateral	Vertical	Lateral	Vertical
a	Synthetic	0.23	0.76	0.21	0.78
	Real	0.24	0.74	0.15	0.7
b	Synthetic	0.25	0.75	0.17	0.82
	Real	0.25	0.75	0.21	0.6
c	Synthetic	0.24	0.75	0.01	0.01
	Real	0.25	0.74	0	0.08
d	Synthetic	0.24	0.75	0.18	0.79
	Real	0.25	0.75	0.1	0.62
Average Error		0.01	0.003	0.121	0.235
Standard Deviation		0.007	0.006	0.079	0.301

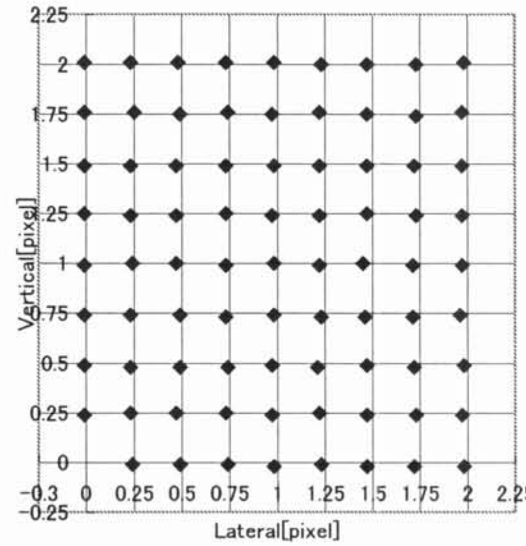

Fig. 10 Detection results for the proposed method for various image shifts.

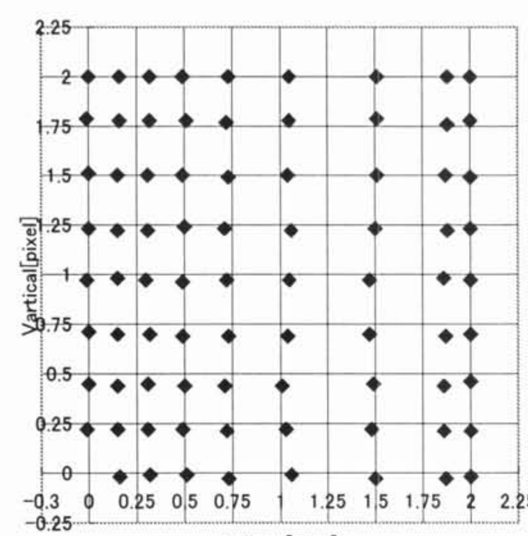

Fig. 11 Detection results for POC for various image shifts.