Illumination sensitivity of joint transform correlators using differential processing: computer simulation and experimental studies

G.S. Pati, K. Singh *

Photonics Group, Department of Physics, Indian Institute of Technology, Delhi, New Delhi 110016, India

Received 7 July 1997; accepted 30 September 1997

Abstract

Differential and binary differential joint-transform correlators are found to be associated with high tolerance to illumination variation of the reference and target. This makes them suitable for illumination-independent pattern recognition applications. Computer simulation results show that a tolerance limit as high as an amplitude ratio of 0.25 between the target and the reference image can be attained. As a refinement to the above mentioned techniques, we suggest the use of isotropic difference operators. We also present some experimental results for the differential type JTCs.

Keywords: Joint-transform correlator; Differential processing; Illumination-independent target detection

1. Introduction

Joint transform correlator is an early architecture proposed by Weaver and Goodman [1] and Goodman [2] for optically convolving two functions. Since its inception, the technique has undergone many modifications in order to yield better performance in real-time optical pattern recognition. Among some of the potential techniques are the use of nonlinearity in the joint power spectrum [3] (JPS), spatial synthesis of reference function [4], gradient preprocessing [5] on the input image, fringe adjusted technique [6], and cosine wave encoding [7], etc. Recently, Zhong et al. [8] have proposed a new method known as a differential JTC (DJTC) in which a finite difference operation has been applied to the JPS. The difference being a high pass operation, eliminates the undesired dc spot formed at the centre of the correlation peaks. Although the differential operation is difficult to be realized optically, it can be implemented digitally with less computation than in case of a binary JTC [9,10] based on adaptive, median or local-median thresholding. The differential JTC will have a bipolar JPS. A binarized version of a DJTC can be easily generated observing the sign change in the JPS. Being more light efficient, it is found to yield higher correlation peak intensity [8].

In the present paper, we have studied an important hidden aspect of a differential JTC and binary differential JTC (BDJTC). This aspect is concerned with their sensitivity to illumination imbalance between the reference and target in a JTC. Although not fully insensitive, this class of JTCs possesses a low sensitivity to illumination difference as they suppress the relatively slow variation of bias across the fringes formed in JPS. This is a useful property associated with these JTCs and makes them favourable for pattern recognition applications under circumstances which have been dealt with in many papers [11–13]. The bipolar form of differential and binary differential JPS makes them unsuitable for display on amplitude-only spatial light modulators (SLMs). In an attempt to implement these JTCs using an amplitude mostly SLM, we have added suitable bias to the respective bipolar JPSs in order to make them positive. Although this operation does not change the characteristics of differential type JTCs, it generates a dc term in the correlation plane.
2. Principle

The input image $f(x, y)$ to a differential JTC consists of a reference $r(x, y)$ and a target $s(x, y)$ situated at two different positions in the input plane:

$$f(x, y) = r(x + x_0, y) + s(x - x_0, y).$$  \hspace{1cm} (1)

For such an input image, the intensity signal detected at the Fourier plane is given by

$$E(u, v) = |R(u, v)|^2 + |S(u, v)|^2 + 2R(u, v)S(u, v) \times \cos \left[ \phi_s(u, v) - \phi_r(u, v) + 2 \alpha_a \right].$$  \hspace{1cm} (2)

where $(u, v)$ are the coordinates in the frequency domain, $R(u, v)$, $\phi_s(u, v)$ and $S(u, v)$, $\phi_r(u, v)$ are the amplitude

---

Fig. 1. (a) Object used as reference and target, (b) input image showing target and reference with amplitude ratio $a = 0.25$; three dimensional plots showing correlation results for (c) classical, (d) differential, (e) binary differential JTCs.
and phase of the Fourier transforms (FTs) of \( r(x, y) \) and \( r(x, y) \), respectively. The JPS given in Eq. (2) contains interference fringes formed over the Fourier spectra of reference and target images. These interference fringes form the correlation signal in the output plane after a second step FT. Consider a case when the illumination of the target, which is identical to the reference, differs from the reference. If \( a \) (0 \( \leq a \leq 1 \)) is the amplitude ratio between the target and the reference, then the normalized JPS is given by

\[
E^a(u, v) = \frac{|R(u, v)|^2}{|R_{max}|^2} \left[ 1 + a^2 + 2a \cos(2 \pi u_0 v) \right].
\]  

(3)

where \( R_{max} \) is the maximum value of \( R(u, v) \). The correlation signals which correspond to the FT of the third term in Eq. (3) are given by

\[
C^a(x, y) = \frac{2a}{|R_{max}|^2} \left( 1 + a^2 \right)^2 \text{FT} \left[ |R(u, v)|^2 \cos(2 \pi u_0 v) \right] = \frac{a}{|R_{max}|^2} \left( 1 + a^2 \right)^2 \left\{ [r \otimes r] \odot \delta (x - 2u_0) \right. \\
\left. + [r \otimes r] \odot \delta (x + 2u_0) \right\}. 
\]  

(4)

where symbols \( \otimes \) and \( \odot \) denote correlation and convolution, respectively. It shows that the correlation intensity for a classical JTC is dependent on amplitude ratio \( a \) through a factor \( a^2/(1 + a^2)^2 \). Due to such a dependence, the correlation signal intensity falls rapidly with a small change in amplitude ratio \( a \) between the target and the reference image. Such a dependence poses a problem in real-world pattern recognition applications where the target illumination is not under control and could differ from that of the reference.

The fringe contrast or modulation depends on the magnitude of the bias term. In a DJTC, a differentiation is carried out on JPS prior to obtaining the correlation results. Although the fringes in the JPS do not have abrupt transition of amplitude values across them, they are enhanced by the difference operation resulting in improved contrast. Since the derivative always assumes a maximum in the direction of the edge (i.e., the direction perpendicular to the fringes), the derivative along the direction \( a \) (line joining the reference and target objects) has been taken. A continuous derivative of the JPS in Eq. (3) is given by

\[
E_a(u, v) = \frac{\partial |R|^2}{\partial u} \left[ 1 + a^2 + 2a \cos(2 \pi u_0 v) \right] \\
- 4a \pi u_0 |R|^2(u, v) \sin(2 \pi u_0 v) \\
= -4 \pi u_0 R^2(u, v) \sin(2 \pi u_0 v),
\]  

(5)

\(|R(u, v)|^2\) is a slowly varying distribution compared to the cosine fringes. The magnitude of \( \partial |R|^2/\partial u \) is small compared to \( |R(u, v)|^2 \). Thus, the correlation signal generated from the above JPS will be independent of \( a \), i.e.,

\[
C^a(x, y) = -\frac{\pi u_0}{|R_{max}|^2} \text{FT} \left[ |R(u, v)|^2 \sin(2 \pi u_0 v) \right]. 
\]  

(6)

Since we have used the slowly varying approximation for \( |R(u, v)|^2 \), we can not expect a complete illumination invariance from a differential JTC. But it is expected to exhibit low sensitivity or in other words high tolerance to illumination variation between the reference and target. The Fourier transform of a differential JPS also yields correlation output without a dc term, as the differentiation is equivalent to multiplying a filter with transfer function \((-jx)\) in the correlation plane.

A binary version of a DJTC which is more light efficient, can be obtained binarizing the bipolar differential JPS retaining its sign as follows.

\[
E_a(u, v) = \begin{cases} 
  +1: & E_a(u, v) > 0, \\
  -1: & E_a(u, v) \leq 0.
\end{cases}
\]  

(7)

Such a JTC inherits all the characteristics of a DJTC accompanying sharp and intense correlation peaks compared to a DJTC.

3. Simulation results

We present the computer simulation results to show relatively lower sensitivity of differential and binary differential JTCs to illumination imbalance between reference and target. For our simulation study and later on in experimental study, we have chosen an object shown in Fig. 1a. The size of each object in the input image is \((38 \times 33)\) pixels. For our study, an amplitude ratio \( a \) of 0.25 has

![Fig. 2. Plots showing the sensitivity of classical and differential type JTCs to variation in amplitude ratio between target and reference.](image-url)
been created between the target and reference in the input plane (Fig. 1b). A standard \((128 \times 128)\) point FPT routine has been used to compute the correlation results. Fig. 1 shows the correlation results obtained for classical, differential, and binary differential JTCs. In order to draw a comparison between them, the correlation results are normalized with respect to the total energy in the output plane.

The correlation peak obtained in a classical JTC (Fig. 1c) becomes weak in intensity and gets overshadowed by the autocorrelation dc generated at the centre. The peak intensity falls by \(\approx 70\%\) of its value for an ideal situation corresponding to \(a = 1\). However, for a DJTC, the correlation peak stays sufficiently higher in intensity across a reduced dc margin (Fig. 1d). The drop in magnitude of correlation peak intensity is \(\approx 45\%\) in this case. The correlation result obtained for BDJTC shows further improvements resulting in a gain in correlation intensity by a factor of 40 compared to DJTC. The correlation peak is found to drop only by \(\approx 22\%\) from an ideal situation. This set of results confirms the fact that the differential type JTCs are less susceptible to illumination variation across the reference and the target due to reasons discussed earlier.

The curves shown in Fig. 2 amply demonstrate the above feature of differential type JTCs over a range of \(a\), i.e., \((0.25 \leq a \leq 1)\). In applications where such an illumination difference is likely to occur, the differential type JTCs are expected to yield better performance as they can safely tolerate an amplitude variation of \(\approx 75\%\) between target and reference. When the target is presented under extremely poor illumination condition, i.e., \((a < 0.25)\), the
correlation intensity falls rapidly for both DJTC and BDJTC. This is due to the fact that the smoothed bias starts becoming increasingly dominant in governing the fringe modulation in differential JPS again.

As an improvement in the implementation of these JTCs, we propose the use of isotropic difference operators [1–4] for obtaining a differential JPS. The results shown in Fig. 1 make use of such an operator. Normally in JTC, the reference and target windows are pre-defined in the input plane. The target is often captured live through a video camera and displayed in the target window. Since the target to be identified could fall anywhere inside the target window, the magnitude of one-dimensional difference will depend on the position of the target inside the window. If the target is situated along a direction other than the direction of difference, the magnitude of difference falls, thereby affecting the correlation strength. For example, a differential JTC using a forward difference along a horizontal direction, produces a peak intensity which falls by a margin of 30% when the target is oriented at an angle of 60° with respect to the u direction inside the window keeping its distance from the centre of the reference window the same. Such an effect can be expected to be present in the results shown by Zhong et al. [8] for high discrimination characteristic of BDJTC with two different targets. A different position chosen for one of the targets other than that along the horizontal direction might reduce the correlation strength obtained for the nontarget, although the effect is predominantly due to high discrimination characteristic possessed by differential processing.

To overcome such a problem, one can use isotropic difference operators, such as two gradient masks (\(1 - 1\) and \([1 - 1]\)). The magnitude of the difference is then calculated using absolute sum of values obtained from these two masks. Fig. 3 shows the null effect of target orientation on the correlation results obtained from a DJTC

---

**Fig. 5.** Correlation results obtained from a classical JTC in (a) ideal situation \((α = 1)\), (b) nonideal situation \((α = 0.25)\); from a differential JTC in (c) ideal situation \((α = 1)\), (d) nonideal situation \((α = 0.25)\). The solid lines shown in the figures correspond to the intensity scan in terms of grey values.
using two gradient masks. The result shows actual correlation values. The disadvantage of such a method is that it doubles the cost of computation and generates unwanted distributions around the dc term. Use of second order isotropic difference Laplacian operator described by a single mask can help in reducing the computation, but will be more sensitive to the presence of noise in the target image [14].

4. Experimental

The experimental set-up used to implement the differential and binary differential JTCs is shown in Fig. 4. The image used earlier for simulation has been used in the experiment except the fact that the reference and the target images are positioned in the horizontal direction. An SLM has been used to display the image in the input plane to the JTC. It has a high VGA resolution (640 × 480), but has a limited grey scale capability. Due to such a limitation, we preferred to create an illumination variation through the use of a neutral density filter placing it in front of the target image as shown in Fig. 4, rather than reducing the grey level across the target image. A diode-pumped mini Nd:YAG laser (λ = 532 nm) has been used to generate an expanded collimated beam which illuminates the SLM. A half-wave plate is used in the input beam, allowing us to optimize the contrast in the displayed image. A 50 cm focal length Fourier transform lens is used to observe the Fourier spectrum of the input image. The joint power spectrum is then captured through an 8-bit CCD camera.

The limited dynamic range of CCD poses a problem. However, the weak fringes formed at high frequencies are faithfully captured allowing the intense low frequency fringes to saturate. In order to implement a DJTC, the JPS is processed using difference masks. The resulting JPS is added with a suitable bias which is found through a maximum search. For a BDJTC, the differential JPS is binarized to values 1 and 0 instead of 1 and –1. Since the sign in the JPS encodes the relevant information, this mode of implementation will not reflect true characteristics of a BDJTC. For a proper implementation, one requires a binary SLM working in phase modulation mode.

The processed JPSs are displayed on the SLM and a second step FT yields the correlation results. Fig. 5 shows the results obtained from a classical JTC. The figures also show the intensity scan across the correlation plane. The correlation planes are processed in order to eliminate the unwanted scattering noise formed around the broad central spot, thereby giving a better view of the intensity distribution across the correlation peaks. Fig. 5a shows the result in an ideal situation. Fig. 5b shows the result when an illumination variation of 0.25 is created across the target and reference. The correlation peaks are not visible in this case, thereby showing its high sensitivity to illumination variation. Fig. 5c shows the correlation peaks along with the intensity scan for a DJTC in an ideal situation. Fig. 5d shows the results obtained from a DJTC when a = 0.25. It clearly shows its lower sensitivity to illumination variation. For a BDJTC, the SLM used for displaying the JPS is fed with patterns corresponding to grey value of 255 (for 1) and 0. This leads to some undesired phase modulation across the JPS and results in different intensity distributions in correlation peaks formed on either side of the dc (Fig. 6). The binarization also leads to the generation of higher harmonics which are not shown in the figures for the sake of clarity. We have chosen the brightest of the correlation peaks and shown the intensity scan across it. Although the correlation profiles are expected to be sharper, they do not appear so due to the present SLM characteristics. The figures in Fig. 6 still show a higher tolerance to illumination variation for such a JTC.

5. Conclusion

In this paper, we have studied an important aspect of differential and binary differential JTCs proposed recently. Besides their capability to produce higher correlation peaks, and discrimination ratio and to eliminate the strong undesired dc term, they have shown to possess a low sensitivity to variation of illumination across the target and reference which, otherwise, adversely affects the correlation performance of a classical JTC. We have also tried to implement these JTCs in a hybrid experimental set-up using amplitude mostly SLM and produced experimental results supporting the above fact.

Acknowledgements

The authors wish to acknowledge the assistance from the Council of Scientific and Industrial Research (CSIR) and Planning Commission, Government of India.
References