Quantization and Truncation Conditions of Fourier Power Spectrum for Good Performance in Binary Subtracted Joint Transform Correlator

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(Received July 7, 1995; Accepted April 16, 1996)

Binary subtracted joint transform correlator (BSJTC) provides sharp autocorrelation peaks and better discrimination for similar targets even though many reference images are arranged regularly in an input scene. The effects of the number of reference patterns, the quantization levels and truncation of the Fourier power spectra on the performance of BSJTC are investigated. The number of effective quantization levels to obtain sharp and clear autocorrelation peaks is estimated by computer simulations using the input scenes with many binary images (alphabetic characters) and half-tone images (human portraits). Experimental results of BSJTC are also shown using a hybrid system with a Bi$_2$SiO$_5$ spatial light modulator and a personal computer.

Key words: pattern recognition, optical information processing, joint transform correlation, Fourier transformation, spatial light modulator, laser, Bi$_2$SiO$_5.$

1. Introduction

The joint transform correlator (JTC)$^{1-3}$ is known to be a useful tool for pattern recognition. Many JTC process algorithms have been proposed to improve the correlation signals. Javidi and Horner$^4$ proposed a correlator that uses thresholding at both the input and the Fourier planes and compared the performance of this binary JTC (BJTC) with the classic JTC. Javidi$^5$ further investigated nonlinear JTCs (the hard-clipping BJTC and the k-th law clipping BJTC) and provided analytical expressions for the thresholded joint power spectrum. Kuo$^6$ investigated a BJTC using the error function limiter, and Inber employed error diffusion to improve the binarization method in BJTC.$^6$

The BJTC provides a higher peak intensity, narrower correlation width and better discrimination for similar targets compared with the classic JTC. One important advantage of pattern recognition using an optical system is parallel treatment of many images. However, the BJTC has problems arising many crosscorrelation signals between the reference patterns when many of the latter are used. Authors proposed a method to remove the intra-class correlations called "binary subtracted joint transform correlator (BSJTC)"$^{7-9}$ and the method was shown to be useful even for pattern recognition using a few tens of reference images regularly arranged. Cheng et al.$^{10}$ proposed a similar method independently.

Experimentally, there have been several reports$^{11-16}$ on the recognition results using 3-16 patterns in BJTC. Authors showed that a hybrid BSJTC system using a Bi$_2$SiO$_5$ spatial light modulator (BSO-SLM) and a personal computer was advantageous in recognition using a large number of binary reference images and half-tone reference images, because the optical system has high resolution and BSO-SLM has a good gray-level representation property. The recognition of alphabetic characters using 52 reference images and human portraits using 22 reference images were demonstrated.$^{21}$

In the BJTC and BSJTC, we need to detect the joint power spectrum and convert to binary optical transmission of amplitude or phase. The resolution of intensity of the joint power spectrum is an important factor in the performance of both correlators. Javidi et al.$^{17,18}$ made a mathematical analysis of the quantization and truncation effects using an object and a reference patterns. They also estimated the quantization and truncation conditions for the optimized correlation signal$^{18}$ but not the relation between the conditions and the shape of the correlation peak. To apply the JTCs for practical image recognition, it is necessary to analyze the quantization and truncation effects using many reference patterns and to estimate the required conditions to generate a sharp and high correlation peak.

This paper investigates the effects of quantization and truncation in the BSJTC using numerous reference patterns. The quantization and truncation conditions to generate a sharp and high correlation peak are estimated theoretically in the next section. These results are compared with simulation results quantitatively using alphabetic characters as binary images and human portraits as half-tone images in Sect. 3. Experimental results are described in Sect. 4.

2. Binary Subtracted Joint Transform Correlator

The BSJTC is briefly explained and the quantization and truncation effects are discussed theoretically. The input scene of BSJTC consists of object and reference images. The joint power spectrum $|F(u,v)|^2$ of the input scene is given by

\[ |F(u,v)|^2 = |F_0(u,v)|^2 + |F_1(u,v)|^2 + 2F_0(u,v)F_1(u,v)\cos((x_0-x)v + (y_0-y)v) + 
\]

\[ -\phi_0(u,v) + \phi_1(u,v), \]

(1)

where $(u,v)$ are the spatial frequency coordinates and $F_0(u,v)\exp[i\phi_0(u,v)]$ and $F_1(u,v)\exp[i\phi_1(u,v)]$ correspond to the Fourier transforms of the object signal $o(u,v)$
located at \((x_v, y_v)\) and the reference signal \(r(x, y)\) located at \((x_r, y_r)\), respectively. When the input or the reference signal consists of many patterns, the power spectrum \(|F|^2\) contains the intra-class interference terms between the object or the reference patterns. For simplicity in the following, we assume that the reference signal consists of many patterns \((K\) patterns\):

\[
r(x, y) = \frac{1}{K} \sum_{k=1}^{K} r_k(x-x_u, y-y_u)
\]

and

\[
F_i(u, v) \exp\left[i\phi_i(u, v)\right] = \frac{1}{K} \sum_{k=1}^{K} R_k(u, v) \exp\left[i\phi_k(u, v)\right] \times \exp\left[-i(x_u u + y_u v)\right],
\]

where \(R_k(u, v)\) and \(\phi_k(u, v)\) are the amplitude function and the phase function of the Fourier transform of \(r_k(x, y)\), respectively. Thus the joint power spectrum is expressed as

\[
|F(u, v)|^2 = |F_0(u, v)|^2 + \left|\sum_{k=1}^{K} F_k(u, v) R_k(u, v) \cos\left[(x_u x - x_k)u + (y_u y - y_k)v - \phi_k(u, v) + \phi_0(u, v)\right]\right|^2.
\]

The intra-class interference terms can be removed by subtracting the power spectrum \(|F|^2\) of reference signal from the joint power spectrum. In BSJTC, the subtracted power spectrum \(S(u, v)\)

\[
S(u, v) = |F(u, v)|^2 - |F_0(u, v)|^2 - \left|\sum_{k=1}^{K} F_k(u, v) R_k(u, v) \cos\left[(x_u x - x_k)u + (y_u y - y_k)v - \phi_k(u, v) + \phi_0(u, v)\right]\right|^2
\]

is calculated, and the spectrum \(S(u, v)\) is binarized with the thresholding level at zero. The correlation signal between the input and the reference signals are obtained by the inverse Fourier-transforming the spectrum \(S(u, v)\). In this method, only the interference fringes between the Fourier-transform wavefronts of object and reference signals are extracted successfully. So, the correlation signals between the object and the references are preserved but the intra-class correlation signals between the references.

From Eq. (3), the phase function \(\phi_i(u, v)\) is written as

\[
\tan\phi_i(u, v) = \frac{\sum_{k=1}^{K} R_k(u, v) \sin\left[\phi_k(u, v) - (x_u u + y_u v)\right]}{\sum_{k=1}^{K} R_k(u, v) \cos\left[\phi_k(u, v) - (x_u u + y_u v)\right]}.
\]

Using this phase function, the subtracted power spectrum \(S(u, v)\) is rewritten as

\[
S(u, v) = 2F_0(u, v) F_i(u, v) \sum_{k=1}^{K} R_k(u, v) \times \cos\left[(x_u x - x_k)u + (y_u y - y_k)v - \phi_k(u, v) + \phi_0(u, v)\right]
\]

The bipolar image \(B(u, v)\) is made from \(S(u, v)\) by hard-clipping as values

\[
B(u, v) = \begin{cases} 
1 & \text{for } S \geq 0 \\
-1 & \text{for } S < 0
\end{cases}
\]

and is developed in the Fourier series:

\[
B(u, v) = \sum_{k=1}^{K} \sum_{m=1}^{\infty} C_m(u, v) \cos\left[m \frac{2\pi}{M} (x_u x - x_k)u + (y_u y - y_k)v - \phi_k(u, v) + \phi_0(u, v)\right]
\]

where

\[
C_m(u, v) = \frac{1}{\pi} \lim_{T \to \infty} \int_{-T}^{T} \omega^{-1} J_m(2\omega R(u, v) F_i(u, v)) d\omega
\]

and \(J_m\) is the Bessel function. Performing the integration in Eq. (10), we obtain

\[
B(u, v) = \sum_{k=1}^{K} \sum_{m=1}^{\infty} \frac{4i^{2m}}{(2m+1)\pi} \cos\left[(2m+1)\{(x_u x - x_k)u + (y_u y - y_k)v - \phi_k(u, v) + \phi_0(u, v)\}\right]
\]

The term contributing the first-order diffraction in \(B(u, v)\) is written as

\[
B_1(u, v) = \sum_{k=1}^{K} \frac{4}{\pi} \cos\left[(x_u x - x_k)u + (y_u y - y_k)v - \phi_k(u, v) + \phi_0(u, v)\right]
\]

and in the case of \(\phi_0(u, v) = \phi(u, v)\) the first-order diffraction becomes proportional to

\[
\text{FT}^{-1} \left[ \frac{4}{\pi} \cos\left[(x_u x - x_k)u + (y_u y - y_k)v\right]\right]
\]

where \(\text{FT}^{-1}\) means inverse Fourier transform. This equation expresses that BSJTC gives the same response as phase only matched filtering. The fringes \(S(u, v)\) before hard-clipping consist of superposition of many sinusoidal fringes with different spatial frequencies, phase and directions. The weights of superposition, \(R_k(u, v) / F_i(u, v)\) \((k = 1, 2, \ldots, K)\), will be equalized and become proportional to \(1/K\) as \(K\) increases, when the patterns \(r_k\) belong to the same class and have about the same brightness.

Next, the effects of quantization and truncation in the Fourier plane on the correlation signal are considered. In the BJTC and BSJTC, the joint power spectrum is quantized, subtracted and binarized with electronic circuits. The quantization error deteriorates the shape of the autocorrelation signal and causes noise. In the BJTC, the critical number of quantization levels, which means the minimum number to obtain the correlation signal, was investigated using an object and a reference pattern. In the following, the required quantization and truncation condition to obtain sharp and high correlation peaks suitable for pattern recognition is determined using many reference patterns. The binarized joint power spectrum becomes randomly destroyed by the quantization noise. Sufficient of quantization levels should be chosen to reduce the noise and to obtain a good correlation signal; in reality, however, there is a limit to the possible number of quantization levels. The truncation is effective in reducing the quantization noise by means of a limited number of quantization levels. In general the joint power spectrum \(|F|^2\) has larger values at lower spatial frequency and becomes maximum at zero spatial frequency (the 0th order component). The intensity modulation due to the interference fringes in the joint power spectrum is much weaker than the 0th order component. To obtain the correlation signal, the 0th order component should be truncated while the interference fringes at lower spatial frequency region are lost, and the low intensity interfer-
ence fringes should be detected with an adequately small quantization interval. We assume that the 0-th order component of the spectra has been truncated by a factor $M$ and the intensity level at the zero frequency after truncation has also been quantized to $N$ bits, where the truncation factor $M$ was defined as the ratio of the intensity of joint power spectrum $F_{\text{max}}^2$ at the zero frequency to the intensity level after truncation $F_0^2$. In this case, the quantization interval has been set to $F_0^2/2^N$. This interval is equal to $F_{\text{max}}^2/2^N$, where

$$L = \log_2 M + N.$$ (15)

The joint power spectrum is quantized into $2^L$ levels in this case. As described above, the quantization interval of the low intensity interference fringes in the joint power spectrum essentially decides the quality of the correlation signals. The effects of quantization and truncation should be standardized with $L$.

In practical pattern recognitions, though required quality of the correlation peaks depends on the design of the signal detection equipment of the pattern recognition system, the autocorrelation peak should, of course be sharper and higher for practical use. The required quantization and truncation condition should be estimated considering the following conditions: (a) the full width at half maximum (FWHM) of the autocorrelation peak becomes about one pixel, (b) the peak height of the autocorrelation signal grows up sufficiently and saturates with increasing quantization levels. The term “autocorrelation” is used here for the correlation signal between the object pattern and the reference pattern with the same shape and brightness as the object. The width of the correlation peak depends on the area size of the binarized interference fringes which function as a diffraction grating. To achieve condition (a), the interference fringes in all frequency regions on the Fourier plane must be quantized and binarized. The joint power spectrum using many references includes many intra-class interference fringes. To obtain the correlation signal, the quantization interval should be narrower than the amplitude of the intensity variation of each interference between the object and each reference. From Eq. (4), the amplitude $A(u,v)$ is

$$A(u,v) = 2F_0(u,v)R_0(u,v).$$ (16)

When the patterns $o$ and $r_s$ belong to the same class and have about the same brightness, $A$ is approximately written as

$$A(u,v) = 2|F_o(u,v)|^2.$$ (17)

The required quantization and truncation condition can be estimated from Eq. (17) as

$$F_{\text{max}}^2/2^L < 2|F_o(u,v)|^2.$$ (18)

From Eq. (18) the effective value $L_n$ achieving condition (a) should meet the following equation in all $(u,v)$ regions,

$$L_n > \log_2 (F_{\text{max}}^2/|F_o(u,v)|).$$ (19)

The quantization noise causes diminution of the correlation peak height. To achieve condition (b), the quantization noise should be minimized, and the amount of the quantization levels $L$ should be enough to transmit the characteristics of the input scene. Then, $L$ should be equal to or more than the amount of information that is evaluated by the numbers of pixels and intensity levels in the input scene. The effective value $L_n$ achieving condition (b) can be roughly estimated by

$$L_n = (\text{the number of pixels in the input scene}) \times (\text{the maximum intensity levels of the input scene}).$$ (20)

3. Simulation

To confirm the theory of the preceding section, processings of BSJTC were simulated in a computer using input scenes including many reference images and an object image. Two kinds of input scenes with various numbers of reference images were prepared for the simulations: an input scene with binary images of alphabetic letters such as shown in Fig. 1 (a) and a halftone scene with images of human portraits such as shown in Fig. 1 (b). The intensity levels of the binary and halftone scenes were 1 and 8 bits, respectively. The input scenes had $512 \times 512$ pixels. The object image was set at the center of the scene, and the reference images were arranged surrounding the object image.

Simulations were carried out as follows. First, the joint

![Fig. 1. Examples of input scenes. The image at the center of the scene was used as an input image (object image) and regularly arranged images as reference images. (a) with binary images and (b) with halftone images.](image-url)
power spectrum \( |F(u,v)|^2 \) and the power spectra \( |F_s(u,v)|^2 \) and \( |F_r(u,v)|^2 \) were calculated with double precision floating-point number which has enough precision for considering the value of \( M \) and \( N \).

Next, \( |F(u,v)|^2 \), \( |F_s(u,v)|^2 \) and \( |F_r(u,v)|^2 \) were quantized with the number of quantization levels \( N \) and the truncation number \( M \). Third, the subtracted spectrum \( S(u,v) \) was calculated and binarized by zero thresholding level. Finally, the correlation peaks were obtained by inverse Fourier-transforming the binarized spectrum.

The results of simulations for the binary images are shown in Figs. 2-8. The available area of the binary images in the simulations was \( 64 \times 64 \) pixels/image. Figure 2 shows the results of the variation in the autocorrelation peak heights versus the number of reference patterns at the various values of \( M \) and \( N \). As \( L \) increases, the peak heights increase and their rate of diminution decreases. Figure 3 shows the distributions of autocorrelation and crosscorrelation peaks in the output signal plane for sev-

Fig. 2. Variations of autocorrelation peak height versus number of reference patterns \( K \) in case of input scene with the same binary image shown in Fig. 1(a) for various \( M \) and \( N \).

Fig. 3. Output signal images under (a) \( M=100 \) and \( N=8 \) bits \((L=14,7)\), (b) \( M=1 \) and \( N=16 \) bits \((L=16)\), (c) \( M=1000 \) and \( N=8 \) bits \((L=18)\), (d) \( M=1 \) and \( N=18 \) bits \((L=18)\), in case of input scene with binary images shown in Fig. 1(a). Where the signals are binarized by thresholding with 1/10 level of the autocorrelation peak height.

Fig. 4. 3-D representations of output signals containing autocorrelation peaks and surrounding area in case of the binary image shown in Fig. 1(a). (a) shows representing area, hatched region, in the output signal plane. (b)-(d) show the signals for \( M=100 \) and \( N=8 \) bits \((L=14,7)\), \( M=1000 \) and \( N=8 \) bits \((L=18)\), and \( M=1 \) and \( N=18 \) bits \((L=18)\), respectively. In each figure, the highest peak is the autocorrelation peak of the letter \( U \). The autocorrelation peak height is normalized to a constant height, and the next higher peak is the crosscorrelation between the letters \( U \) and \( O \).
eral cases. Three-dimensional (3-D) displays of the autocorrelation peaks for the three cases shown in Fig. 3 are shown in Fig. 4. From Figs. 3 and 4, it is seen that (1) the ratios of autocorrelation peak height to crosscorrelation peak height and noise signal increase as $L$ increases and discriminability of the autocorrelation signal also increases, and (2) we can obtain the output signals with similar quality even under different truncation factors if the effective numbers $L$ are the same. Variations in the autocorrelation peak heights for various values of $M$ and $N$ are summarized in Fig. 5 using the effective number $L$.

This figure shows that the truncation of $M \leq 1000$ does not affect the autocorrelation peak height even though the interference fringes in the lower spatial frequency region are eliminated; the truncation has a similar effect to increasing the number $N$. This is true of all the results shown in the following, this fact is kept. Variations of FWHM, the ratio of the autocorrelation peak height to the maximum noise peak (the signal-to-noise ratio; S/N) and the ratio of the autocorrelation peak height to the maximum peak height of crosscorrelation peaks (the ratio of auto-to-cross correlation) versus $L$ are shown in Figs. 6-8. The autocorrelation peak becomes sharp and the crosscor-

Fig. 5. Variations of autocorrelation peak heights versus effective number of quantization levels $L$ for three input scenes with number of reference patterns $K=1$, 10 and 52, in the case of the binary images. Symbols $\circ$, $\triangle$, $\diamond$ and $\triangle$ show the results in the cases of truncation factor $M=1$, 10, 100 and 1000, respectively.

Fig. 6. Variations of full width at half maximum of autocorrelation peak height versus effective number of quantization levels $L$ in the case of the binary images.

Fig. 7. Variations of the S/N versus effective number of quantization levels $L$ in the case of the binary images for two input scenes with number of reference patterns $K=10$ and 52. Symbols $\circ$, $\triangle$, $\diamond$ and $\triangle$ show the results for truncation factor $M=1$, 10, 100 and 1000, respectively.

Fig. 8. Variations of the ratio of autocorrelation peak height to crosscorrelation peak height versus effective number of quantization levels $L$ in the case of the binary images for two input scenes with number of reference patterns $K=10$ and 52. Symbols $\circ$, $\triangle$, $\diamond$ and $\triangle$ show the results for truncation factor $M=1$, 10, 100 and 1000, respectively.
relation peaks and noises decrease, as the effective number \( L \) increases.

Similar simulations were performed using the halftone image shown in Fig. 1(b). The available area and quantization levels of the halftone images in the simulations were \( 85 \times 96 \) pixels/image and 256 levels, respectively. Variations of the autocorrelation peak height versus \( L \) are shown in Fig. 9. Output signals for several cases are shown in Figs. 10 and 11. The output signal rises and becomes sharper as \( L \) is increased. Variations of the halfwidth of the autocorrelation peak, S/N and the ratio of auto-to-cross correlation versus \( L \) are shown in Figs. 12-14.

From the variation of FWHM (Fig. 6 and 12), the effective numbers of quantization levels \( L_n \) are obtained. The values \( L_n \) can also be calculated using Eq. (19) and \( |P_n| \) of each object pattern as discussed in the previous section. The calculated results are shown in Table 1 com-

Fig. 9. Variations of autocorrelation peak height versus effective number of quantization levels \( L \) in the case of input scene with the halftone images shown in Fig. 1(b) for various \( M \) and \( N \). Symbols ○, △, ◊ and ▲ show the results in the cases of truncation factor \( M = 1 \), \( 10 \), \( 100 \) and \( 1000 \), respectively.

Fig. 10. Output signal images under (a) \( M = 1000 \) and \( N = 8 \) bits (\( L = 18 \)), (b) \( M = 1000 \) and \( N = 12 \) bits (\( L = 22 \)), (c) \( M = 10 \) and \( N = 20 \) bits (\( L = 23 \)), and (d) \( M = 1 \) and \( N = 24 \) bits (\( L = 24 \)) in the case of input scene with the halftone image shown in Fig. 1(b). Where the signals are binarized by thresholding level with a proper low intensity level.

Fig. 11. 3-D representations of output signals containing autocorrelation peaks and surrounding area in case of the halftone image shown in Fig. 2(a). (a) shows represented area, hatched region, in the output signal plane. (b)-(d) show the signals for \( M = 1000 \) and \( N = 8 \) bits (\( L = 18 \)), \( M = 10 \) and \( N = 20 \) bits (\( L = 23 \)), and \( M = 1 \) and \( N = 24 \) bits (\( L = 24 \)), respectively. The highest peak in each figure shows the autocorrelation peak of the input image. The autocorrelation peak height is normalized to a constant height, and the other peaks show the crosscorrelation peaks or noise peaks.
pared with the simulation results, and agree well in each case. From the variation of autocorrelation peak height (Figs. 5 and 9), the effective number of quantization levels $L_e$ is obtained. The values $L_e$ can also be calculated using Eq. (20). The calculated and simulated results are shown in Table 1, and agree well. From Table 1, it is evident that the theoretical analysis is consistent with the simulation results. For the input scenes of binary images and half-tone images: (1) at the values $L_e$ given in Table 1, S/Ns in Figs. 7 and 13 became larger than 3 and 10, and the ratio of auto-to-cross correlations in Figs. 8 and 14 became larger than 5 and 50; (2) at the values $L_e$ given in Table 1, the S/Ns in Figs. 7 and 13 became larger than 100 and 10, and the ratio of auto-to-cross correlations in Figs. 8 and 14 became larger than 50 and 50, respectively. Thus, when the

Fig. 12. Variations of full width at half maximum of autocorrelation peak height versus effective number of quantization levels $L_e$ in the case of input scene with the 22 halftone reference images. Symbols ○ and △ show the half widths in the horizontal and the vertical directions, respectively.

Fig. 13. Variations of S/N versus effective number of quantization levels $L_e$ in the case of the halftone images for two input scenes with number of reference patterns $K = 3$ and 22. Symbols ○, ■ and △ show the results in the cases of truncation factor $M = 1$, 10, and 1000, respectively.

Fig. 14. Variations of the ratio of autocorrelation peak height to crosscorrelation peak height versus effective number of quantization levels $L_e$ in the case of the halftone images of two input scenes with number of reference patterns $K = 3$ and 22. Symbols ○, ■ and △ show the results for the cases of truncation factor $M = 1$, 10, and 1000, respectively.

Table 1. List of $L_e$ obtained from simulation and Eq. (19) and $L_e$ obtained from simulation and Eq. (20).

<table>
<thead>
<tr>
<th>Number of images in input scene</th>
<th>Input scenes with binary images</th>
<th>Input scenes with halftone images</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$L_e$ simulations (bit)</td>
<td>$L_e$ simulations (bit)</td>
</tr>
<tr>
<td></td>
<td>$L_e$ (bit)</td>
<td>$L_e$ (bit)</td>
</tr>
<tr>
<td></td>
<td>Eq. (19) (bit)</td>
<td>Eq. (20) (bit)</td>
</tr>
<tr>
<td>2</td>
<td>12</td>
<td>14</td>
</tr>
<tr>
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<td>25.5</td>
<td></td>
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</tbody>
</table>

quantization and truncation conditions of the joint power spectrum satisfy the $L_e$ and/or $L_e$, the deterioration of the shape of the autocorrelation peak and the noise signal caused by the crosscorrelations and quantization error can be reduced and BSJTC gives good performances. Furthermore, it is shown that the truncation of the joint power spectrum is useful to increase the effective quantization levels in a real BSJTC system.

4. Experiment in Optical System

The effects of the quantization and the truncation in the Fourier plane on the performance of BSJTC were also investigated experimentally using the hybrid system. The system consisted of an optical system and a personal computer, the former was composed of a laser scanner, a BOS-SLM and a lens for Fourier transform. The input scenes were written in BOS-SLM using the laser scanner. The image was written in BOS-SLM around 0.2 second using an Ar ion laser with 488 nm wavelength and 10 mW output intensity. The scenes were read out using a He-Ne laser and Fourier transformed optically. The Fourier power spectra were measured photometrically by a CCD
(charge coupled device) camera and converted to digital data by A/D converter. The quantization level $N$ was limited to 8 bits by both the S/N of the CCD camera, used, 50 dB (≈300:1) and the number of quantization levels of the A/D converter, 8 bits.

The number of effective pixels in the optical system was more than $500 \times 700$. This resolution and the potential of halftone representation property in BSO-SLM made it possible to recognize an alphabetic character and a portrait in BSJTC with a few tens of reference patterns.

In the experiment, the value $M$ of the truncation factor was changed by adjusting the readout light intensity from the He-Ne laser. To increase $N$, 256 sequential frames of data of each power spectrum from the CCD camera were integrated numerically in the computer. The accidental error was thus reduced and a substantial value of $N$ was equal to 12 bits ($-8 \text{ bit} + 4 \text{ bits} = \sqrt{256}$). This method was applied to confirm the effect to increase $N$. In a practical system, a CCD camera and an A/D converter with sufficient specifications should be chosen for the required effective number of quantization levels $L$.

Figure 15 (a) shows the experimental results of variations of the autocorrelation peak height using binary images similar to those shown in Fig. 1(a). Figure 15 (b) also shows the results of the variations using halftone images similar to those shown in Fig. 1(b). Figure 16 (a) 

![Figure 15](image1.png)  
![Figure 16](image2.png)

**Fig. 15.** Experimental results of variations of autocorrelation peak heights versus number of reference patterns for various $M$ and $N$. (a) and (b) show results using input scenes with binary images as shown in Fig. 1(a) and with halftone images as shown in Fig. 1(b), respectively.

**Fig. 16.** Experimental results of variations of the ratios of auto-to-cross correlation versus number of reference patterns for various $M$ and $N$. (a) and (b) show results using input scenes with binary images as shown in Fig. 1(a) and with halftone images as shown in Fig. 1(b), respectively.
and (b) show the results of the ratio of auto-to-cross correlation using the binary and halftone images. The variations of the autocorrelation peak height and the ratio of auto-to-cross correlations qualitatively agree with the tendencies of the simulation results shown in the previous section. For quantitative confirmation, the MTF (modulation transform function) properties of the optical system must be considered in the simulation and a CCD camera and an A/D converter used with much wider dynamic ranges in the experimental system.

Finally, in order to show the potential of the BSJTC and the hybrid system with the measures described above for expanding the dynamic range of data measurement system in the Fourier plane, we attempted to recognize four persons using twenty reference images: five images with slightly different expressions per person. Figure 17(a) shows an object image at the center and the reference images which consist of two rows in the upper and the lower half planes, respectively. The object image is really the same as the image set at the left end on the upper row in the lower half plane. Figure 17(b) shows the image of output signal obtained by the hybrid system with $M=1000$ and $N=12$ bits, using the image shown in Fig. 17(a). We can clearly see five correlation peaks about the reference images of the same person as the object image and few crosscorrelation peaks about the reference images of other persons, even though the correlation peak heights decrease at the edge of the output plane. This decrease was caused by an insufficient resolution of optical system and can be corrected by using the distance between the object and each reference. The corrected peak heights of each correlation signal are shown in Fig. 18. The corrected peaks about the same person become much higher than those about other persons. The person of the object image could thus surely be recognized and easily distinguished from other persons.

5. Conclusions

The effects of the number of quantization levels and the truncation of the Fourier power spectrum on the performances of the BSJTC were investigated by computer simulation. The formula giving tentative criteria for the effective quantization levels required for both binary and halftone input scenes with an object image and many reference images was introduced. The criteria are given by the condition that the full width at half maximum of the autocorrelation peak becomes smaller than one pixel and that the autocorrelation peak grows up sufficiently and its height reaches saturation.

From the results of simulations and experiments, it is seen that the joint transform correlators with many reference images need precise measurement over a very wide range of intensity in Fourier power spectra. We must develop data measurement equipment with fast response and very wide dynamic range as soon as possible in order to realize useful real-time joint transform correlators. The number of quantization levels and the useful truncation factor should be decided in a practical pattern recognition system according to the number of reference patterns and the kind of target, such as binary patterns of letters and geometrical shapes or halftone patterns of human faces, scenery, animals, etc.

Recognition of individuals was accomplished using a hybrid system with simple measures for expanding the dynamic range of the data measurement system and five portraits per person. We obtained good results suggesting the possibility of applying this system to human recognition.

References