Scale-invariant optical correlators using ferroelectric liquid-crystal spatial light modulators

T. D. Wilkinson, Y. Petillot, R. J. Mears, and J. L. de Bougrenet de la Tocnaye

New experimental results for scale-invariant implementations of the binary phase-only matched filter and the nonlinear joint transform correlator using ferroelectric liquid-crystal spatial light modulators are presented. We provide a comparative study of both architectures for real-time road-sign recognition. Signal-to-peak-noise ratios in excess of 5 dB over a scale range of 1.0 to 2.0 are achieved under realistic conditions of clutter.

1. Introduction

The recent increase in attention paid to real-time correlators is mainly because of the development of new spatial light modulators (SLM's) with better performance and reliability.[1] One of the most significant developments has been in the field of ferroelectric liquid-crystal (FLC) SLM's, as they provide a high contrast ratio at a rapid frame rate. In addition, these devices have been shown to be well suited for implementing both binary phase or amplitude modulation.[2,3] Their characteristics are ideally suited to the application of optical correlators, especially when combined with the possible compactness that the FLC devices can provide when mounted as a silicon backplane device.[4] In addition, recent developments of algorithms based on stochastic iterative optimization procedures[5,6] involving classical optical correlators with invariance properties have enlarged the possible applications for VanderLugt-based optical correlators in the field of complex pattern recognition. The application of FLC SLM's and invariance techniques can be demonstrated through a comparison of two common optical correlator architectures: the binary phase-only matched filter (BPOMF) and the joint transform correlator (JTC). This paper presents a theoretical and experimental comparison of the two optical architectures and demonstrates the feasibility of such architectures in a possible real-time application such as road-sign recognition in a moving vehicle.

T. D. Wilkinson and R. J. Mears are with the Department of Engineering, University of Cambridge, Trumpington Street, Cambridge CB2 1PZ, England. Y. Petillot and J. L. de Bougrenet de la Tocnaye are with the Groupe Optique et Systemes de Communications, Ecole Nationale Superieure Telecom Bretagne, BP 832, Brest Cedex 29285, France.

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2. Correlator Architectures

A. Binary Phase-Only Matched Filter

The BPOMF is a compact linearly aligned architecture that leads to sharp correlation peaks and reliable shift-invariant detection. Figure 1 depicts a particular form of the matched filter known as the modified 4-f correlator.

The collimated laser beam illuminates the input SLM containing the input image, $s(x, y)$, and is Fourier transformed by the first lens to provide the input spectrum, $S(u, v)$, where u and v are coordinates in spatial frequency. The filter, $H(u, v)$, is displayed on the second SLM as a binary phase image.[3] The BPOMF is calculated from the original reference image, $r(x, y)$, by a Fourier transform that is thresholded about an angle δ selected to give the optimum correlation-peak power:

$$H(u, v) = \begin{cases} 0 & \arg[R(u, v)] \leq |\delta| \\ \pi & \text{otherwise} \end{cases}. \tag{1}$$

$R(u, v)$ is the Fourier transform of the original reference image, $r(x, y)$, that is to be correlated with the input image. The spectrum, $S(u, v)$, is multiplied with the filter, and the product is Fourier transformed by a lens to give the correlation output. The output plane is then analyzed to decide if the input and the reference are correlated.

The advantage of using this correlator architecture is that only the desired correlations are generated. The input and the filter are in separate planes to

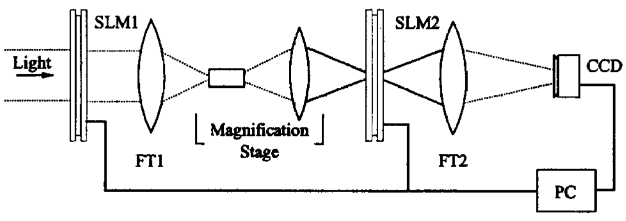


Fig. 1. Modified 4-f BPOMF correlator: FT1, FT2, Fourier-transform lenses; PC, microcomputer.

avoid unnecessary correlation and dc terms. Hence several correlations can be performed with the entire input-plane resolution during one video frame, especially when the fast response times of FLC devices in binary phase mode are used. The BPOMF is also technically simpler; it needs only one light source and is suitable for miniaturization with the inclusion of silicon backplane SLM's.

B. Joint Transform Correlator

As with the BPOMF, the JTC has proven to be suitable for real-time optical pattern recognition.[7] Compared with the classical VanderLugt correlator, the JTC provides higher correlation peaks, better peak-to-sidelobe ratios, and sharper correlation spots.[8] This is due to the nonlinearity in the Fourier plane. Figure 2 provides a description of an all-optical joint transform correlator using an FLC optically addressed SLM (OASLM) as the nonlinear processing element.

The input is an SLM displaying the reference image, $r(x, y) \otimes \delta(x - a, 0)$, and the scene image, $s(x, y) \otimes \delta(x + a, 0)$, where $2a$ is the distance between the two images. The SLM is illuminated by a coherent collimated beam and is Fourier transformed by the first lens. The joint power spectrum, $|S(u, v)\exp(-2j\pi a) + R(u, v)\exp(2j\pi a)|^2$, is formed at the focus of the lens and is written onto the OASLM. In the case of a linear JTC the modulus of the spectrum is read from the OASLM, but for higher-order nonlinear OASLM's such as the FLC device this nonlinearity is a binary thresholding of the modulus. The nonlinearly processed joint power spectrum is read by a second collimated laser beam and is Fourier transformed by the second lens to produce the output correlations. The correlation plane consists of three terms: the central dc term (autocorrelation of the input images) and two symmetric terms, which are the intercorrelations of the reference and the input images, the positions of which are related to the positions of the input and reference.

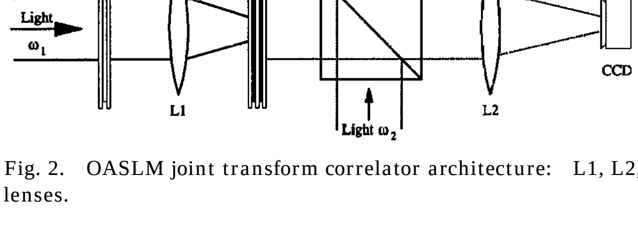


Fig. 2. OASLM joint transform correlator architecture: L1, L2, lenses.

The main advantage of this architecture is the nonlinear processing done by the OASLM in the Fourier plane, providing sharp correlation peaks and very good discrimination capabilities. In particular, it has been shown experimentally[9] that the nonlinear response is close to a kth law, presented by Javidi,[8] and that this OASLM nonlinear characteristic can be modified (severe or smooth) simply by variation of the voltage-driving parameters of the OASLM. Adjustment of the nonlinear response has been shown to enable a good trade-off between filter robustness and selectivity.[9] This architecture is also robust to optical defects within the system. However, the restriction of having to display the input image and the reference in the same plane limits the usable space–bandwidth product (SBWP). This restriction also limits the flexibility of the correlator, especially when the input device is a binary SLM.

3. Invariance

Both the classical BPOMF and the JTC suffer from limited invariance properties when utilized in their simplest forms as pattern-recognition systems. Numerous methods have been proposed to improve their invariance properties.[10] Most of them are analytical solutions, but they do not suit the BPOMF and JTC architectures, as each contains an element of nonlinear performance. Also, practical experience shows that these solutions are difficult to implement and are not particularly robust in an experimental situation. A more logical approach is to use nonlinear techniques to solve the problem of invariance in optical correlators. Recent research has shown techniques such as simulated annealing and the genetic algorithm to be a successful means of achieving invariance in both the BPOMF and the JTC.[2,11]

The nonlinear techniques we developed are similar to the synthetic discriminant function (SDF) approach in that a sequence of reference images is combined to create a filter that contains features from all the original references. In the case of the JTC the SDF filter calculated is a gray-scale image that must be thresholded to suit the FLC devices. The other main difference is that the constraints set in calculating the JTC filter cannot be derived from a mathematical solution to an analytical problem. For the BPOMF the difference is much larger, as the calculation of the filter is done entirely in the filter space (assuming binary phase modulation), unlike the SDF, in which the filter must be transformed and the phase thresholded to get the final filter, causing a degradation in filter performance. In both cases the purpose of the nonlinear optimization technique is to optimize directly for a given SLM device characteristic so that the filter is ideally suited to the correlator construction. The BPOMF is designed directly in binary phase and can be implemented immediately, as can the JTC filter, which is generated for a nonlinear OASLM and is designed for a binary input SLM.

A. Scale-Invariant Binary Phase-Only Matched Filter by Simulated Annealing

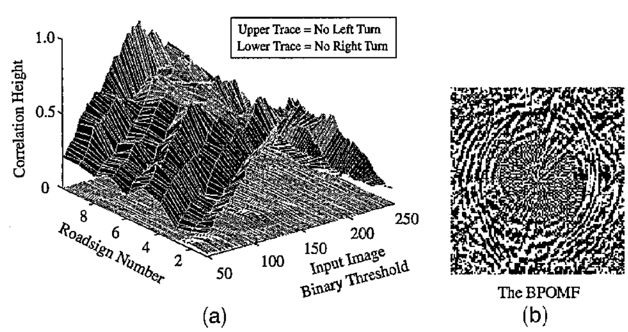
The design of a BPOMF by simulated annealing stems from research on dynamic computer-generated holograms.[12] The idea is to start with a random filter and then anneal down to a working filter. The annealing process is carefully controlled and permits freedom within the optimization algorithm to avoid local minima and to find global minima. The error function to be minimized for correlation over a training set is

$$e = \sum_{k=1}^{Ns} \left\{ \sum_{\text{row}} \sum_{\text{col}} (C_0 - C_k)^2 \right\}, \tag{2}$$

where Ns is the total number of images to be correlated, giving the ideal correlation output intensity of C_0. C_k is the correlation between the annealed filter and the kth reference image to be included in the final filter. C_0 can be either a plane of zeros with a central delta function for images to be recognized or just a plane of zeros that trains the filter to reject images. This is particularly useful when the filter has to differentiate between two closely correlated sets of images (such as the road signs no left and no right turn).

In each loop cycle a randomly positioned pixel is flipped in binary state, and the error is calculated. If the error decreases because of the pixel flip, then the pixel flip remains. If the error increases, then the flip is accepted during the early iterations, but it becomes harder later on as the algorithm progresses. The acceptance of bad changes is governed by the system temperature, which permits descent into a global minima.

The annealed BPOMF shown in Fig. 3(b) has 128×128 pixels. The training set was composed of ten no left (NL) turn signs to be recognized and ten no right (NR) turn signs to be rejected. The NL and the NR signs were edge-enhanced 256-level gray-scale images and varied in size from 49 to 76 pixels (an area scaling of 1.0 to 2.4). The gray-scale was included to improve the performance of the BPOMF when the input scene had to be binarized. The effect of this can be seen in Fig. 3(a), in which the training-set images are thresholded and then correlated with the BPOMF. As a filter constructed from a training set of binary images correlated (more than 3-dB separation between NL and NR) over a threshold range of 112–200, the filter constructed from the gray-scale set had a more uniform threshold coverage of 76–241. The use of the gray-scale training set also greatly improved performance of the BPOMF with signs scaled between those in the training set. The uniformity of the correlations with the training set was 2% but decreased to more than 10% when the training set was binarized. The differentiation between the NL and the NR signs was 6.3 dB. Experimental results are given in Section 4.



(a) (b)

Fig. 3. (a) Training-set correlations with varying binary thresholds at the input image, (b) the BPOMF.

B. Scale-Invariant Joint Transform Correlator

The use of an FLC SLM in the JTC means that binary references must be constructed for the input plane. This constraint strongly limits the range of algorithms that can be used for invariance. A new algorithm that produces binary scale-invariant references has been proposed that ideally suits the JTC.[13] The basic idea of the algorithm is to design filters in the input plane by combination of several views of the same reference. The filter h_1 is built as a linear sum of these input images such that

$$h_1 = \sum_{0}^{Ns} \alpha_i X_i, \tag{3}$$

where X_i is the ith image of the learning base of Ns images. This first filter is gray level, so it must be binarized. This is done by an adaptive thresholding: a pixel will be put to one if its gray level is superior to the mean of its eight nearest neighbors.

Several parameters have to be adjusted carefully to obtain a constant response over the learning base. The size of the sampling region when the adaptive threshold is performed is important. This parameter defines how discriminant the filter will be. The other important parameter to adjust is the weight of each image in the linear combination. This is performed by use of simulated annealing. The criterion optimized is the standard deviation of the peak response over the learning base divided by the average of the peak response over the same base. As optimization is involved in the design, the method is computer intensive but not as much as BPOMF synthesis. These filters are not discriminant when used on a classical JTC architecture. We can take advantage of the nonlinearity of the FLC OASLM in the Fourier plane of the JTC, which improves the selectivity of the filter (as explained in Subsection 2.B). Owing to the presence of a nonlinearity in the Fourier plane (the adjustable nonlinear response of the OASLM), it is preferable that the filter be unselective. The more nonlinear the OASLM, the more selective the JTC will be, which will degrade the performance of the JTC with images in the scale range trained.

The effectiveness of this technique was demonstrated through a series of simulations using road signs captured from an edge-enhancing camera.

Each filter is made by combination of seven training images. The filters are binary and have a resolution of 64 × 64 pixels on the SLM. For all these filters the final cost obtained (standard deviation divided by the average peak response) was less than 1%, which proves the validity of our approach. Experimental results are given in Section 4.

4. Experimental Comparison

The filters generated for the BPOMF and the JTC by optimization were tested in their respective architectures to prove the validity and the robustness of such techniques.

A. Binary Phase-Only Matched-Filter Experiment

The experiment was performed with the modified 4-f correlator in Fig. 1. A 15-mW He–Ne laser beam was launched into a single-mode fiber acting as a spatial filter and was collimated to give a near-Gaussian profile. The transform lenses were f = 250-mm achromats, and the magnification stage was a telescopic pair of achromats of f = 10 mm and f = 400 mm, producing a magnification of 40. The SLM's were both Thorn EMI Central Research Laboratories 128 × 128 FLC devices with 220-μm pixel pitch; the first was used as a binary intensity device, and the second was used as a binary phase device. The output was imaged on a CCD camera.

The correlator output for input NL and NR signs are shown in Fig. 4. The difference between the two correlation peaks is 6.9 dB. The filter was also correlated with the other members of the training set to test the filter's scale-invariant properties. The results of this can be seen in Fig. 5 for a threshold of 130 on the training-set images. The performance is very good, with a small variation between the correlation-peak heights (15%) and 5.9-dB differentiation between the NL and NR image worst case.

The BPOMF was also tested against a more realistic cluttered input containing a NL sign that was not a member of the training set. Figure 6 shows both the input scene and the output from the correlator. A strong correlation peak is clearly visible with a peak-to-noise-peak ratio of 5.2 dB. The BPOMF rejected a similar NR sign with a margin of 5.1 dB; 80

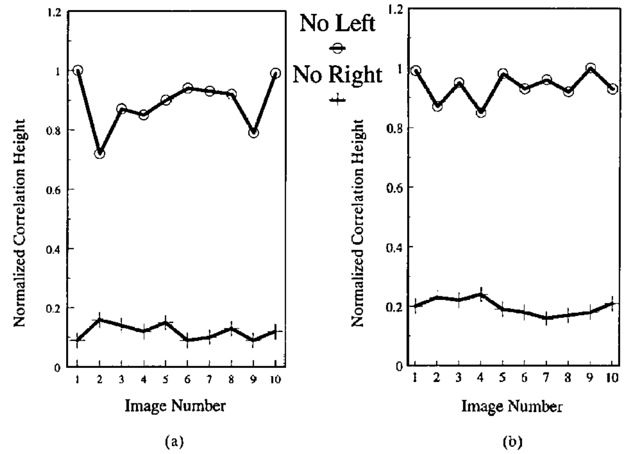


Fig. 5. Scale-invariant BPOMF test: simulation and experiment.

and 60 km/h signs were also tested against the BPOMF and were rejected with greater margins.

B. Joint Transform Correlator Experiment

The experiment was realized on an all-optical JTC (an OASLM in the Fourier plane), shown in Fig. 2. The writing and reading laser was a collimated 30-mW He–Ne laser. The SLM's were both Thorn EMI Central Research Laboratories FLC devices; the first in the input plane was a 128 × 128 electronically addressed SLM, and the Fourier-plane one was a bistable OASLM (with memory) operating with a nonlinearity factor of ~0.3. Owing to its memory capability, the OASLM was used in a transmissive mode, with the same wavelength for both read and write operations. In this case the read and the write operations were performed sequentially. The detection plane was a CCD camera.

As the input SLM is binary and low resolution, preprocessing of the input plane is necessary. For real-time operation, a special edge-enhancing camera was developed at Peugot Societé Anonyme–Citroen for this task. The camera was tested in a vehicle, and a 6-min.-long video film with ~15 different road signs on it was produced. Figure 7 shows a typical scene after processing by the camera. For each reference (i.e., road sign) a sequence of 13 consecutive images was stored, covering a scale factor of 2 in most

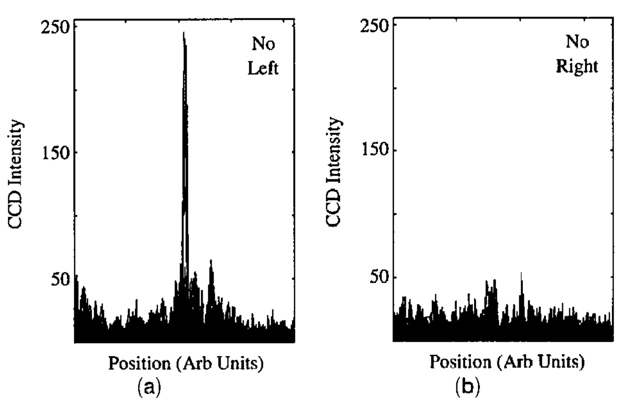


Fig. 4. Experimental correlation profiles of (a) NL and (b) NR signs (number nine in the training set).

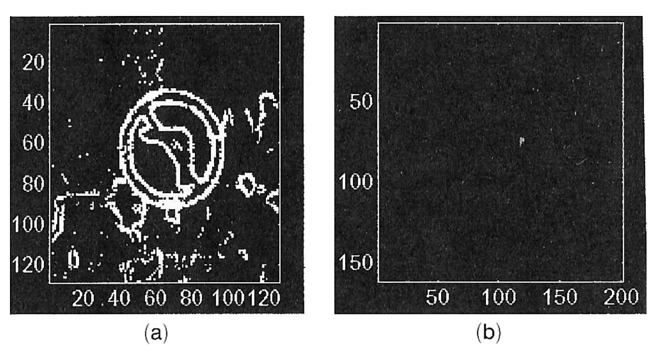


Fig. 6. BPOMF tested under cluttered conditions with nontrained-image (a) input and (b) correlation.

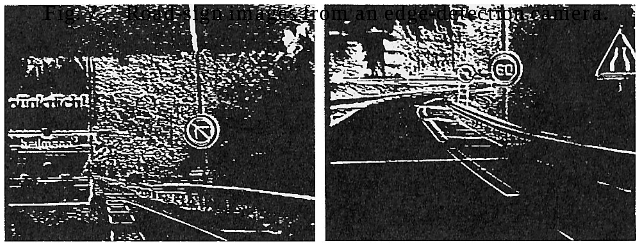


Fig. 7. Road-sign images from an edge-detection camera.

cases. A window of 128 × 128 pixels was extracted to form the final reference-image picture. A special digital signal processor, the TMS C30, was developed in order to extract a 64 × 128 window from the video frame and to send it to the input SLM.

Figure 8 shows the results obtained for the no-left-turn sign. The left-hand side shows what is displayed on the input SLM, and the right-hand side shows the corresponding correlation plane. The total duration of the time sequence was ~1 s. Figure 8 shows three pictures of the sequence, separated by 70 ms. The invariance is clearly demonstrated, and the correlation-peak trajectory can be estimated. Some other parts of the video application without no-left-turn signs were also tested; no correlation was observed. Figure 9 presents a comparison of in-set and out-of-set experimental and simulation results. This shows a good agreement between theory and experiments.

5. Discussion

Use of high-speed FLC SLM's as display devices is shown to be useful for real-time pattern-recognition

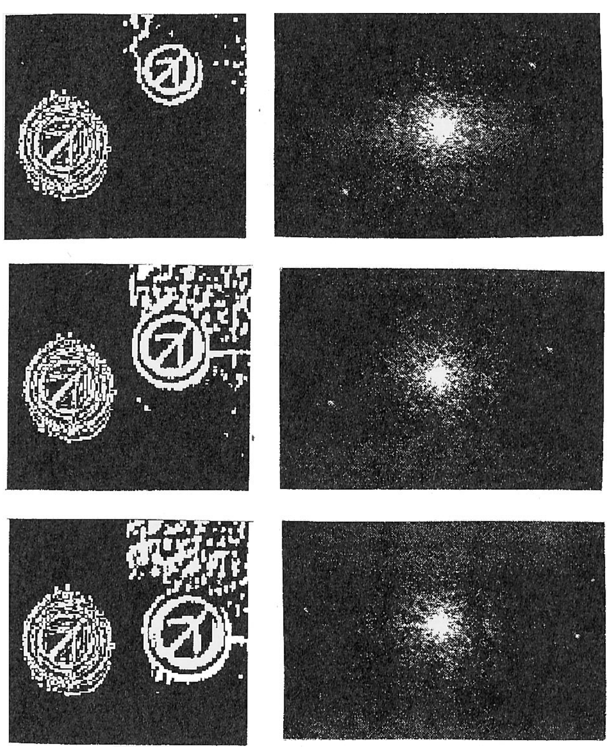


Fig. 8. Scale-invariant JTC experiment.

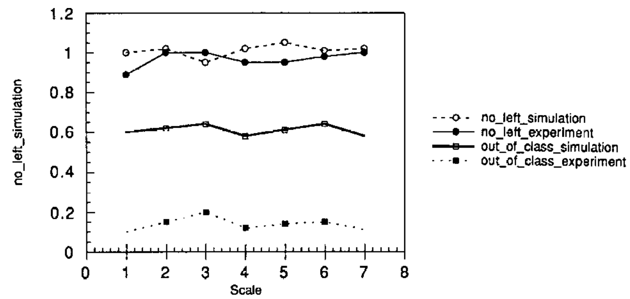


Fig. 9. Scale-invariant JTC test: simulation and experiment.

tasks. Its high repetition rate makes this device competitive owing to the ability to time multiplex the filters with respect to the video rate. However, the bistability can be a limitation, particularly with the JTC architecture. A trade-off between speed and filter capacity must be found for the considered application. Regarding the optical implementation, the BPOMF can be considered as less compact owing to its linear (end-to-end) light path, especially if transmissive SLM's are used. This can be overcome by the use of silicon backplane devices as the input and the filter. The use of invariance techniques has been well documented, with several possible methods being viable. The freedom of having the filter in a separate Fourier plane means that the filter can be made to contain several different features, such as scale invariance. The use of binary phase SLM's means that the correlator can produce sharp peaks with good signal-to-noise ratios, and the separation of input and filter means that only one correlation occurs and can be detected easily. The main problem is the alignment of the filter and the input. This must be done accurately, with the correct scaling, for a correlation to occur. This should not be so significant with a careful choice of architectural implementation. The limits on the SBWP affect the potential invariance that can be implemented in a single filter, but with a high-density filter device, such as a 256 × 256 pixel SLM, this can be avoided.

The JTC is an inherently compact architecture. It is robust, and there are few problems associated with optical alignment. The nonlinear (OASLM) JTC is a fast and powerful correlator. It is capable of producing sharp peaks with good signal-to-noise ratios; it is also easy to implement as an optical system. The problems associated with the JTC lie in the way that the input image is displayed. For current SLM devices this must be in a binary format, which limits the applicability of the JTC. The SBWP of the JTC is also restricted by the need to display the input and the filter side by side, but with modern fast high-density SLM's this will be less of a problem. Invariance implementation in the JTC is possible. The adaptive SDF method as been shown to give very good recognition rates even if the filter capacity is limited owing to binary encoding. An important feature that has not been considered here concerns the output interface between the correlation plane and the decision stage. In the case of the matched filter this is not difficult, as the position of the correlation tells us directly where the sign occurs in the input; hence the only postprocessing needed is a threshold and detection system, such as a line-scanning CCD. In the case of the JTC this is a little more difficult, as the correlation peaks appear in quadrants, which have to be decoded. Solutions have been proposed to overcome this difficulty. One idea consists of focusing each correlation quadrant in a separate spatial region.[15] Hence the input no longer needs to be centered. There is, however, an associated penalty with the correlation signal-to-noise ratio. More generally, possible postprocessing or specially designed detection planes could be advantageously taken into account during the filter optimization procedure. Regarding the compactness of such FLC correlators, compact versions using silicon backplane FLC devices have been proposed successfully.[16] The problem of the dead space surrounding each pixel has to be considered a priority in such a case because this can lead to aliasing if the filter-plane SLM has a lower SBWP than the input SLM. Solutions based on a randomizing of the pixel position within the dead-space area are being investigated[17] that would improve the SLM performance.

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References

1. T. D. Hudson and D. A. Gregory, "Joint transform correlation using an optically addressed ferroelectric liquid-crystal spatial light modulator," Appl. Opt. **29,** 1064–1066 (1990).
2. D. A. Jared, K. M. Johnson, and G. Moddel, "Joint transform correlator using amorphous silicon ferroelectric liquid crystal spatial light modulator," Opt. Commun. **76,** 97–102 (1990).
3. T. D. Wilkinson, D. C. O'Brien, and R. J. Mears, "Scale-invariant binary phase-only matched filter using ferroelectric liquid-crystal spatial light modulators," Appl. Opt. **33,** 4452–4453 (1994).
4. W. A. Crossland, M. J. Birch, A. B. Davey, and D. G. Vass, "Active backplane spatial light modulator using chiral smectic liquid crystal," in *Liquid Crystal Materials, Devices, and Applications*, P. S. Drzaic and U. Efron, eds., Proc. Soc. Photo-Opt. Instrum. Eng. **1665,** 114–127 (1992).
5. U. Mahlab and J. Shamir, "Optical pattern recognition based on convex functions," J. Opt. Soc. Am. A **8,** 1233–1239 (1991).
6. A. Mahalanobis, B. V. K. Vijaya Kumar, and D. Casasent, "Minimum average correlation energy filters," Appl. Opt. **26,** 3633–3640 (1987).
7. B. Javidi and S. F. Odeh, "Multiple object identification by bipolar JTC," Opt. Eng. **27,** 295–300 (1988).
8. B. Javidi, "Nonlinear joint power spectrum based optical correlation," Appl. Opt. **28,** 2358–2367 (1989).
9. A. Kohler, B. Fracasso, P. Ambs, and J. L. de Bougrenet de la Tocnaye, "Joint transform correlator using nonlinear ferroelectric liquid crystal spatial light modulator," in *Optical Information Processing Systems and Architectures III*, B. Javidi, ed., Proc. Soc. Photo-Opt. Instrum. Eng. **1564,** 236–243 (1991).
10. D. Casasent, D. Psaltis, and E. Wolf, "Deformation invariant space variant optical pattern recognition," in *Progress in Optics*, E. Wolf, ed., (North-Holland, Amsterdam, 1978), Vol. XVI, pp. 289–356.
11. Y. Petillot, G. Keryer, and J. L. de Bougrenet de la Tocnaye, "An optimal reference filter study for an optical JTC," presented at the French-Israeli Workshop on Optical Computing, Tel Aviv, 16–17 December 1992.
12. T. D. Wilkinson, D. C. O'Brien, and R. J. Mears, "Dynamic asymmetric binary holograms using a FLC SLM," Opt. Commun. **109,** 222–226 (1994).
13. M. Roe, K. Schehrer, R. Dobson, and L. Schirber, "Distortion invariant optical pattern recognition using composite filters, in *Optical Pattern Recognition IV*, D. P. Casasent, ed., Proc Soc. Photo-Opt. Instrum. Eng. **1959,** 203–213 (1993).
14. L. Guibert, G. Keryer, and M. Attia, "Optical road sign recognition to improve active safety features," in *Optical Pattern Recognition IV*, D. P. Casasent, ed., Proc. Soc. Photo-Opt. Instrum Eng. **1959,** 230–236 (1993).
15. Q. Tang and B. Javidi, "Technique for reducing the redundant and self-correlation terms in joint transform correlation," Appl. Opt. **32,** 1911–1918 (1993).
16. R. M. Turner, D. A. Jared, G. D. Sharp, and K. M. Johnson, "Optical correlator using very-large-scale-integrated circuit ferroelectric liquid-crystal electrically addressed spatial light modulators," Appl. Opt. **32,** 3094–3101 (1993).
17. S. Heddle, D. Vass, and R. Sillitto, "Reduction of aliasing in correlation using pixellated SLM's," in *Optical Information Processing Systems and Architectures IV*, B. Javidi, ed., Proc. Soc. Photo-Opt. Instrum. Eng. **1772,** 116–127 (1992).