Pattern recognition with an adaptive phase-input joint transform correlator

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ABSTRACT

An adaptive phase-input joint transform correlator for real-time pattern recognition is presented. A reference image for the correlator is generated with a new iterative algorithm based on synthetic discriminant functions. The obtained reference image contains the information needed to discriminate reliably a target against known false objects and a cluttered background. Calibration look-up tables of all used opto-electronic elements are included in the design of the adaptive phase-input joint transform correlator. The resulting joint input image for the correlator is a real-valued bipolar image, which cannot be directly displayed with a conventional amplitude-only spatial light modulator. Commonly two optical correlations and post-processing are used. We utilize a phase-only spatial light modulator in the input plane. A new phase-only joint input image is obtained by a monotonic mapping the intensity to phase information. The phase-only image is easily introduced into an optical setup. In this case we need just one correlation and no post-processing. Experimental results are provided and compared with those obtained with computer simulations.

Keywords: joint transform correlator, adaptive correlation filters, synthetic discriminant functions, intensity to phase mapping, spatial light modulators

1. INTRODUCTION

Correlation based pattern recognition has attracted considerable attention in the last decades because correlation filters can be implemented optically or by the use of hybrid (opto-digital) systems at high rate. A common way to design correlation filters is optimization of various performance criteria. The filter performance can be substantially improved by the use of an adaptive approach, i.e., designing a filter with good performance characteristics for a given observed scene with a fixed set of patterns or a fixed background to be rejected, rather than a filter with average performance parameters over an ensemble of images. In many real applications objects to be recognized are embedded in high-cluttering backgrounds. The presence of distortions like in-plane rotations or scale changes makes the detection process a very difficult task for classic correlation filters. The use of synthetic discriminant functions (SDF) for distortion invariant pattern recognition became a very popular technique. SDF technique with a simple set of properly selected training images synthesizes a filter possessing the invariance to arbitrary geometric distortions of a target, while analytical filters are able to provide the invariance only to scale-changes and in-plane rotations of a target, respectively. Hybrid systems commonly use liquid crystal displays (LCD) as spatial light modulators (SLM). The SLM’s can operate at high-rate and can be easily configured either as amplitude-only modulator (AOM) or as phase-only modulator (POM). Note that SLM’s provide flexibility that pure-optical systems don’t possess. Opto-digital systems can be implemented in two principal architectures: the 4f correlator and the joint transform correlator (JTC). An advantage of the JTC comparing with 4f correlator is that the former is less sensitive to misalignments of an optical setup such as scale, horizontal, vertical and azimuth differences between input and frequency planes. A common SDF filter is a real-valued bipolar image, which cannot be directly displayed on a conventional LCD.
working in amplitude-only mode. Recently, an adaptive joint transform correlator (AJTC) for real-time distortion invariant pattern recognition was proposed. The AJTC is able to detect reliably a known target (including distorted versions) against false known objects when are embedded in high-cluttering backgrounds. The reference image is obtained with an iterative algorithm, which utilizes information about a target, objects to be rejected (including a background), and calibration look-up tables of all opto-electronic devices. Since the designed reference image is a bipolar real-valued image, two optical correlations and a post-processing are usually required. In this paper we propose a new AJTC, which requires only one correlation and no post-processing. The proposed AJTC utilizes a input SLM in the phase-only mode. A new phase-only joint input image is created with the help of an iterative design process. The new AJTC is referred to as an adaptive phase-input joint transform correlator (APIJTC). The following of this paper is organized as follows: In Section 2 we provide a brief review of the classic joint transform correlator and the adaptive joint transform correlator. Section 3 presents a design procedure of the APIJTC. In Section 4 computer simulations are provided and discussed. Section 5 explains an experimental hybrid setup and shows the obtained experimental results. These results are compared with those obtained with computer simulations. Section 6 summarizes our conclusions.

2. JOINT TRANSFORM CORRELATORS

2.1. Classic Joint Transform Correlator

In this architecture the input plane (joint input image) \( f(x, y) \) consists of a scene image \( s(x, y) \) displayed alongside of a reference image \( t(x, y) \), separated by a distance \( \pm d \) each with respect to the origin. The scene image can contain objects (desired and non-desired objects), which are embedded into a background. The joint image can be written as

\[
    f(x, y) = s(x, y - d) + t(x, y + d).
\]

The joint power spectrum (JPS) obtained (for instance with a CCD camera) is given by

\[
    E(\mu, \nu) = |S(\mu, \nu)|^2 + |T(\mu, \nu)|^2 + S(\mu, \nu)T^*(\mu, \nu) \exp(-i2d\nu) + S^*(\mu, \nu)T(\mu, \nu) \exp(i2d\nu),
\]

applying the inverse Fourier transform to Eq. (2), we obtain

\[
    c(x, y) = s(x, y) \otimes s(x, y) + t(x, y) \otimes t(x, y) + s(x, y - 2d) \otimes t(x, y - 2d) + s(x, y + 2d) \otimes t(x, y + 2d),
\]

where "\( \otimes \)" denotes the correlation operation. It can be seen from Eq. (3) that the auto-correlations of the scene and target images mainly contribute at the origin, whereas the cross-correlations terms, which are terms of interest, are placed at the distances \( \pm 2d \) with respect to the origin. A drawback of the classical JTC is its poor discrimination capability due to a high bias-level in the joint power spectrum, also it present a extremely low tolerance to noise and to object distortions.

2.2. Adaptive Joint Transform Correlator

The AJTC is an hybrid pattern recognition system that ensures a high correlation peak corresponding to the target while suppressing possible false peaks, which can be caused by any non-desired object or a background. A reference image for the correlator is generated with the help of an iterative algorithm based on SDF. A basic SDF filter is defined as follows:

\[
    h = R(R^+R)^{-1}c,
\]

Here, \( R \) is a matrix with \( N \) columns and \( M \) rows (number of pixels for each training image), where its \( i \)th column represent a vector version of the training image \( s_i(x, y) \), and \( c \) represent a column vector of \( c_i \), where \( \{c_i, i = 1, 2, ..., N\} \) are prespecified values in the correlation output at the origin for each training image. At each iteration the algorithm suppresses the highest sidelobe peak and, therefore, monotonically increases the value of
discrimination capability until a prespecified value will be reached. Discrimination capability (DC) is one of the most important performance measures in pattern recognition and it is formally defined as follows\(^2\):

\[
DC = 1 - \frac{|C_B(0,0)|^2}{|C_T(0,0)|^2},
\]

(5)

where \(|C_B|^2\) is the maximum of intensity in the correlation plane over the area of background to be rejected, and \(|C_T|^2\) is the maximum of intensity in the correlation plane over the area of target position. The area of target position is determined in the close vicinity of the actual target location. The area of background is complementary to the area of target position. The proposed iterative procedure used for the AJTC is given as follows:

1. Create a basic SDF filter trained only with the target, using Eq. (4).
2. Create the input image (see Eq. (1)) by composing the SDF filter and the image to be rejected (background or a non-desired object).
3. Carry out the joint transform correlation taking into account the calibration look-up tables of all opto-electronics devices such as real SLM and CCD camera.
4. Calculate the DC using Eq. (5).
5. If the value of the DC is greater or equal to the desired value then the filter design procedure is finished, else, go to the next step.
6. Create a new object to be rejected from the background. The origin of the object is at the highest sidelobe position in the intensity correlation plane. The region of support of the new object is the union of the shapes of all objects involved in the process (desired and non-desired objects). The object is included into the false class of objects.
7. Design a new SDF filter utilizing two-class recognition problem. The true class contains only the target and the false class consists of the false class objects. Go to step 2.

In this manner we explicitly employ the definition of the DC for the filter design until a desired value of the DC is reached. Note that with this adaptive approach we control the entire correlation plane.

2.2.1. Opto-digital implementation

The opto-digital implementation of the AJTC is based on the classic JTC setup. This means that the joint input image is recorded into an AOM, which is able to work only with non-negative images. One of the methods is a bipolar decomposition of the reference image \(h(x,y)\) as follows:

\[
h(x,y) = h^+(x,y) - h^-(x,y),
\]

(6)

where

\[
h^+(x,y) = \begin{cases} h(x,y) & \text{if } h(x,y) \geq 0 \\ 0 & \text{otherwise} \end{cases}
\]

(7)

and

\[
h^-(x,y) = \begin{cases} h(x,y) & \text{if } h(x,y) < 0 \\ 0 & \text{otherwise} \end{cases}
\]

(8)

In this case the intensity of the cross-correlation between the input-scene \(s(x,y)\) and the reference image \(h(x,y)\) can be written as follows\(^5\):

\[
c(x,y) = |s(x,y) \odot h(x,y)|^2 = |s(x,y) \odot [h^+(x,y) - h^-(x,y)]|^2
\]

\[
= |s(x,y) \odot h^+(x,y)|^2 + |s(x,y) \odot h^-(x,y)|^2 - 2 \left[|s(x,y) \odot h^+(x,y)|^2 \right]^{1/2} \left[|s(x,y) \odot h^-(x,y)|^2 \right]^{1/2}.
\]

(9)

It can be seen from Eq. (9) that we need two correlations and a simple point-wise post-processing to obtain the desired correlation plane.
3. ADAPTIVE PHASE-INPUT JOINT TRANSFORM CORRELATOR

Phase-only filters are widely used in optical pattern recognition because they provide a high light efficiency and produce sharp correlation peaks.\textsuperscript{21,22} Phase-only filters can be easily recorded on a conventional LCD configured as a POM. The POM can modulate any signal within the range of about $[-\pi, \pi]$ with an acceptable linearity.\textsuperscript{23} Note that in this manner any bipolar phase-only image may be modulated. A commonly used intensity to phase transformation can be written as follows\textsuperscript{14,24}:

$$
\phi_f = \exp\left[ i\pi \frac{f(x, y) - G_{\min}}{G_{\max} - G_{\min}} \right],
$$

(10)

where $\phi_f$ is the phase-only image, $f(x, y)$ is the input intensity-image, $G_{\max}$ and $G_{\min}$ are the highest and lowest values of $f(x, y)$, respectively. Experimental results with a phase-encoded input JTC were reported.\textsuperscript{25,26} Our aim here is to investigate effects of phase-encoding in the iterative filter design process. A schematic diagram of the APIJTC architecture is shown in Fig. 1. A coherent linearly-polarized light-beam passes through the beam spliter (BS). Two new beams are collimated by the lenses ML1, L1 and ML2, L3 to illuminate two different optical systems. The first optical system consists of the LCD1 (configured in the phase-only modulation regime), the Fourier transform lens L2, and the square-law detector Camera1. Note that the phase-only modulation can be achieved by setting the optical axis of the linear polarizer P1 parallel to the molecular director of the LCD1.\textsuperscript{9,23} The second system consists of the LCD2 (configured in the amplitude-only modulation regime), the Fourier transform lens L4, and the square-law detector Camera2. To set the LCD2 as an AOM we align the optical axis of the polarizers P2 and P3 perpendicular with respect to the molecular director of the LCD2. The phase-encoded joint input image is recorded onto the LCD1. Camera1 takes the JPS and sends it to a nonlinear device, and its output is displayed on the LCD2. Next Camera2 captures the correlation intensity plane. Note that in real applications it is very difficult to obtain a linear joint transform correlation because of nonlinearity owing to the SLM and CCD camera responses. This is why we introduce in the diagram of the APIJTC a nonlinear device, which takes into account nonlinear effects in the reference image design procedure. A main drawback of the JTC architecture is that the JPS possesses a high bias-level, which may saturate the detector. This leads to losing high-frequency information, and, therefore, affecting the discrimination capability of the system. Let us show that the bias-level in amplitude modulation is lower than that of phase-only modulation. Let $f(x, y)$ be an intensity encoded joint input image like in Eq. (1) with the range of $[-1, 1]$. The phase-encoded version of $f(x, y)$ can be written as follows:

$$
\phi_f(x, y) = \exp[\mp f(x, y)].
$$

(11)

The Fourier transform of $f(x, y)$ is

$$
F(\mu, \nu) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f(x, y) \exp[-i(\mu x + \nu y)] \, dx \, dy.
$$

(12)
Note that the bias-level of the JPS can be described as follows:

\[ \text{bias}_f = \langle F(0,0), F^*(0,0) \rangle \]
\[ = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} |f(x,y)|^2 \, dx \, dy, \]  
\( (13) \)

where the symbol "\langle, \rangle" denotes the inner product, and \( F(0,0) \) is the Fourier transform of \( f(x,y) \) evaluated at the origin. For the phase-only image the Fourier transform is

\[ \Phi(\mu, \nu) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \exp \{ i \pi [s(x,y) - (\mu x + \nu y)]] \} \, dx \, dy. \]
\( (14) \)

The bias-level can be written as

\[ \text{bias}_\Phi = \langle \Phi(0,0), \Phi^*(0,0) \rangle \]
\[ = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} dxdy. \]
\( (15) \)

Since illumination almost fully passes through a POM (LCD has a minimal absorption) then in most cases \( (\text{bias}_\Phi >> \text{bias}_f) \). Therefore, in phase-only mode a detector of the JPS will be saturated at low-frequencies area. On the other hand, an advantage of the phase transformation is that the auto-correlation peaks is never lower than cross-correlation signals, due to the amplitude normalization. The output cross-correlation peak intensities are given by

\[ c(0, \pm 2d) = \left| \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \phi_s(x,y)\phi_h(x,y) \, dx \, dy \right|^2 \]
\[ = \left| \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \exp \{ i\pi [s(x,y) - h(x,y)] \} \, dx \, dy \right|^2. \]
\( (16) \)

If \( s(x,y) = h(x,y) \), i.e., the auto-correlation case, then \( c(0, \pm 2d) = \text{bias}_\Phi \). So a sidelobe in the cross-correlation area is lower than the auto-correlation peak. For the classic JTC the auto correlation peak is equal to \( \text{bias}_f \). Since we consider an input scene with a cluttered background, it is likely that a sidelobe is higher than the auto-correlation peak. Therefore, the use of phase-only input scenes may improve the DC. Now we can describe an iterative algorithm for the APIJTC. A block diagram of the proposed procedure is shown in Fig. 2. It is given as follows:

1. Create a basic SDF filter trained only with the target, using Eq. (4).
2. Create the input image (see Eq. (1)) by composing the designed SDF filter and the image to be rejected (background or a non-desired object).
3. Perform the monotonic intensity to phase mapping of the image created in step 2 (using Eq. (10)). Take into account the calibration look-up table of the POM.
4. Carry out the Fourier joint transformation of the input plane and record the JPS.
5. Transform the JPS with a nonlinear \( k \)-th-law point-wise function. Here, the nonlinear coefficient is determined by the calibration look-up table of the AOM.
6. Calculate the DC using Eq. (5).
7. If the value of the DC is greater or equal to the desired value then the filter design procedure is finished, else, go to the next step.
8. Create a new object to be rejected from the background. The origin of the object is at the highest sidelobe position in the intensity correlation plane. The region of support of the new object is the union of the shapes of all objects involved in the process (desired and non-desired objects). The new object is included into the false class of objects.

9. Design a new SDF filter utilizing two-class recognition problem. The true class contains only the target and the false class consists of the false class objects. Go to step 2.

3.1. Opto-Digital Implementation

The output of a SLM in phase-only modulation regime is a complex signal with amplitude normalization to one. The JPS may contain information about an input scene, a reference object, as well as the energy of an unused area in the SLM. This is a problem because the bias-level of the JPS becomes much higher than for the case of the classic JTC. A common solution to this problem is to insert a \( \{n \times m\} \)-pixels block at the center of the JPS before performing the Fourier transform. Another solution is based on the modulation property of the Fourier transform. We encode the unused area of the SLM with a periodic phase-mask with intention to diffract its spectrum to an unused high frequencies area to be consequently filtered.\(^{27}\) A new phase-only joint input image can be written as follows:

\[
\hat{\phi}_f(x, y) = \phi_s(x, y) + \phi_h(x, x) + b(x, y)\exp[i(xm_x + ym_y)], \tag{17}
\]

where \(\phi_s(x, y)\) and \(\phi_h(x, y)\) are the phase-only scene and the reference image respectively, \((m_x, m_y)\) are modulation frequencies, and \(b(x, y)\) is the unused area of the SLM, which is defined as follows:

\[
b(x, y) = \begin{cases} 
0, & \text{within the } \phi_s(x, y) \text{ and } \phi_h(x, y) \text{ area} \\
1, & \text{otherwise}
\end{cases}. \tag{18}
\]

Now, the JPS is given by

\[
\hat{E}(\mu, \nu) = |\Phi_s(\mu, \nu)|^2 + |\Phi_h(\mu, \nu)|^2 \\
+ \Phi_s(\mu, \nu)\Phi_h^*(\mu, \nu)\exp(i2\nu d) + \Phi_h(\mu, \nu)\Phi_s^*(\mu, \nu)\exp(-i2\nu d) \\
+ |B(\mu-m_x, \nu-m_y)|^2 \\
+ \Phi_s(\mu, \nu)B^*(\mu-m_x, \nu-m_y)\exp(i\nu d)
\]
Figure 3. (Left) Phase-response of LCD1 used for experiments. (Right) Intensity-response of LCD2 used for experiments.

\[ E(\mu, \nu) \approx |\Phi_s(\mu, \nu)|^2 + |\Phi_h(\mu, \nu)|^2 + \Phi_s(\mu, \nu)\Phi_h^*(\mu, \nu)\exp(i2\nu d) + \Phi_h(\mu, \nu)\Phi_s^*(\mu, \nu)\exp(-i2\nu d). \]  

(19)

(20)

4. COMPUTER SIMULATIONS AND EXPERIMENTAL RESULTS

In this section we present results obtained with the proposed APIJTC. The first step is to determine calibration look-up tables of SLM’s used in the laboratory. These tables contain information about the dynamic range of signals as well as the degree of nonlinearity introduced by SLM’s and CCD camera. Fig. 3(Left) shows the phase response of the LCD1, while Fig. 3(Right) shows the amplitude response of the LCD2. From Fig. 3(Left) we see that a signal range of [0, 119] corresponds to a phase-shift of [0, \pi] can be obtained, whereas for a signal range of [120, 255] corresponds to a phase-shift of ([\pi, 7/4\pi]). On the other hand, from Fig. 3(Right) we observe that the dynamic range of LCD2 is [0, 48] gray-scale levels. This curve has a nonlinear behavior, which can be approximated by a kth-law non-linear device with output = (input)^{1/k}, and k = 1.8. This information is used in the proposed iterative algorithm to generate a reference image for the correlator.

4.1. COMPUTER SIMULATION RESULTS

To test the performance of the proposed method we generate a reference image from a test image shown in Fig. 4(Left). The image contains two butterflies with the same shape but with different information contents. The target is the butterfly located in the upper-left corner. The size of the scene image is 128x128 pixels and the size of the target is about 60x37 pixels. The signal range of the images is [0, 255]. After 24 iterations, a reference image with DC=0.8 was obtained. The phase-only image encoded according to the response of LCD1 is shown in Fig. 4(Right). The intensity distribution obtained with computer simulation is shown in Fig. 5. Note that the target was clearly detected.

4.2. EXPERIMENTAL RESULTS

The experimental results where obtained using the optical setup shown in Fig. 1. The illumination source is generated with an argon laser with wavelength of 488nm. The SLM has a spatial resolution of 832x624 pixels. The CCD camera has resolution of 640x480 pixels. The joint input phase-only image displayed on LCD1 is
Figure 4. (Left) Scene image used for experiments. (Right) Phase-only reference image coded for the LCD1.

Figure 5. (Left) Correlation plane intensity obtained with computer simulation, by testing the scene image shown in Fig. 4(left) with the reference image shown in Fig. 4(right). (Right) Intensity distribution.
Figure 6. Phase-only image displayed in LCD1 for physical experimentation.

Figure 7. (Left) Correlation plane intensity obtained experimentally, by testing the scene image shown in Fig. 4(left) with the reference image shown in Fig. 4(right). (Right) Intensity distribution.

shown in Fig. 6. The correlation plane intensity obtained in the experiment is shown in Fig. 6. The obtained DC is 0.602. Finally note that a conventional phase-only JTC is not able to detect the target.

5. CONCLUSIONS

A new adaptive phase-input joint transform correlator was proposed. A good accordance between computer simulation and experimentation where obtained. The phase-input joint transform correlator is a reliable system to detect a target embedded in a high cluttered background. Moreover, it has ability to distinguish similar objects. To avoid a post-processing and extra correlation a phase-encoding of an input plane was utilized.

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