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Spectral band invariant wavelet-modified MACH filter

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ABSTRACT

Filters synthesized with images of a specific spectral band in general fail to recognize targets in a different spectral band. In this paper, we therefore demonstrate the use of the wavelet-modified maximum average correlation height (WaveMACH) filter for automatic target recognition applications in both the visible and infrared (IR) spectral bands. As any input target appears different when imaged through two different sensors, i.e., a CCD or an IR camera, a WaveMACH filter synthesized using a CCD image shows no correlation with the image of the same target from an IR camera and vice-versa. Hence, separate filters are required to match the input targets from the two sensors. To avoid the synthesis and storage of separate filters, the images from CCD and IR camera are fused using Daubechies wavelet and then the rotation-invariant WaveMACH filter generated with the fused image. In all, 18 WaveMACH filters (each of 20° range) are required for in-plane rotation invariance in both the spectral bands for the full range of $0–360^\circ$. Computer simulation and experimental results implemented in hybrid digital–optical correlator architecture are shown for the proposed idea. The same filters have also been used to identify multiple targets in a scene. Performance measures like peak-to-sidelobe ratio (PSR), peak correlation energy (PCE) and correlation peak intensity (CPI) have been calculated as metrics of goodness.

1. Introduction

Recognition of images in different spectral bands is a challenging task in pattern recognition applications. The same input target appears dissimilar when imaged through two different sensors, e.g., an infrared (IR) and a CCD camera as the former images the heat radiation emitted by the target whereas the latter images the light reflected from the target. Whereas the performance of a CCD camera is better under good illumination conditions, the IR camera gives a better output under poor illumination or in night conditions, smoke environment or for a moving target. In order to exploit the imaging capabilities in both the bands, it is required to generate a new image in which the information of both the sensors are integrated. Image fusion [1,2] provides the best solution for the above purpose.

The fusion of IR and visual images was described by Toet et al. [3–5] using the pyramidal technique, which produces a fused image by nonlinear recombination of the ratio of low-pass pyramidal decompositions of the original images. It has been shown that better fusion results, both visually and quantitatively, is achieved using wavelet transform [6,7]. In this technique, the main step is the decomposition of the image into its coefficients followed by the coefficient combination to obtain the best quality fused image as explained in literature [8–11].

Pattern recognition using optical techniques have generated considerable amount of interest in the optics community for the last few decades because of its parallel processing capabilities and potential to carry out computations at the speed of light [12–14]. The correlation operation forms the basis of the recognition process and may be interpreted as a measure of similarity for any two images. In a real-time scenario, the target may undergo distortions in the form of rotation, scale changes, etc. Recognition of such distorted images is achieved by the synthesis of distortion-invariant complex matched filters. Two approaches have been reported in literature for in-plane rotation-invariant filter synthesis. The first approach uses the circular harmonic function (CHF) [15], which employs the geometric invariance properties for filter synthesis, whereas the second approach uses a number of rotationally distorted training images for generation of the synthetic discriminant function (SDF) filter [16]. Several variations of SDF have been reported. The MACH filter [17–19] uses the second approach and has been found to be a powerful filter that maximizes the correlation peak height, peak sharpness, while also being tolerant to distortions in the target. The WaveMACH [20] approach proposed recently uses a non-uniform filter range to reduce the number of filters required for in-plane rotation invariance for the full range of $(0–360)^\circ$, which seems impractical from the view of implementation. But none of the

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approaches described above is invariant to images of different spectral bands.

The analysis of the above filters can be optically accomplished through the VanderLugt correlation (VLC) architecture [12,13]. But owing to the design and alignment criticalities in this architecture, a hybrid digital–optical correlator system [21,22] was proposed that allows the potential for a multi-kilohertz reference template search on data acquired at video rates. In this hybrid approach, the input data are digitally Fourier transformed and multiplied with the digitally pre-synthesized distortion-invariant filters. An optical Fourier transform (FT) of the product function produces the correlation output.

In this paper, we exploit the capabilities of WaveMACH approach by making it spectral band invariant as well as of uniform range. Here we demonstrate that 18 uniform range WaveMACH filters are sufficient to provide full $(0–360)^\circ$ in-plane rotation invariance as well as invariance to the visible and IR spectral bands. For this, the images of CCD and IR camera are fused using Daubechies wavelet [9–11] up to level five. The total number of required filters has been decided taking into consideration the rejection threshold for the false class targets as well as the uniform distribution of training set of each filter for both the spectral bands. The WaveMACH filters, each of 20° in-plane rotation range, are synthesized with the fused image of the true class. Analysis of the designed filters was carried out in the hybrid digital/optical correlator architecture to get correlation peaks. Identification of various distorted targets in a multi-target scene has also been shown, using the same filters. Performance measures [23,24] like correlation peak intensity (CPI), peak-to-sidelobe ratio (PSR), and peak correlation energy (PCE) have been calculated as metrics of goodness of the WaveMACH filter. Both simulation and experimental results have been presented.

2. Daubechies wavelet transform and its use in image fusion

The wavelet transform is a powerful tool for multi-resolution analysis [8–10]. The main advantage of using wavelet transform is that it is well suited to manage different image resolutions and allows the image decomposition in different kinds of coefficients, while preserving the image information. The Daubechies wavelet (db4) decomposed up to five levels has been used for image fusion in this paper, since these wavelets are real and continuous in nature and have least root-mean-square (RMS) error compared to other wavelets [8,9]. Daubechies wavelets are a family of orthogonal wavelets defining a discrete wavelet transform and characterized by a maximal number of vanishing moments for some given support. With each wavelet, there is a scaling function (also called father wavelet) which generates an orthogonal multi-resolution analysis. A vanishing moment limits the wavelet's ability to represent polynomial behavior or information in a signal. The Daubechies scaling function $\phi(x)$ and wavelet function $\psi(x)$ [11] both satisfy the following relation in one dimension:

$$\phi(x) = \sum_{i=0}^{N-1} p_i \phi(2x - i) \tag{1}$$

$$\psi(x) = \sum_{i=2-N}^{1} (-1)^i p_{1-i} \phi(2x - i) \tag{2}$$

where p_i ($i = 0,1, \ldots, N-1$) denotes the scaling (low-pass) coefficients, $(-1)^i p_{1-i}$ denotes the wavelet (high-pass) coefficients and N is an even integer. The supports of the scaling function and its corresponding wavelet function are

$$\operatorname{supp} \phi_N = [0, N-1] \tag{3}$$

$$\operatorname{supp} \psi_N = [1 - N/2, N/2] \tag{4}$$

Where, as the wavelet function $\psi(x)$ is good at representing the details and high-frequency parts of an image, the scaling function $\phi(x)$ is good at representing the smooth and low-frequency parts of the image. These analysis and synthesis procedures lead to pyramid-structured wavelet decomposition. The 1-D multi-resolution wavelet decomposition can be easily extended to two dimensions by taking the tensor products of the 1-D scaling and wavelet functions as

$$\begin{aligned} \phi_{LL}(x,y) &= \phi(x)\phi(y), \quad \psi_{LH}(x,y) = \phi(x)\psi(y) \\ \psi_{HL}(x,y) &= \psi(x)\phi(y), \quad \psi_{HH}(x,y) = \psi(x)\psi(y) \end{aligned} \tag{5}$$

Daubechies wavelet transform performed on each source image produces the coefficient maps for each image $I_1(x, y)$ and $I_2(x, y)$. The 2-D wavelet analysis operation consists in filtering and down-sampling horizontally using the 1-D low-pass filter and high-pass filter to each row of the images $I_1(x, y)$ and $I_2(x, y)$, producing the coefficient maps $I_{1L}(x, y)$, $I_{1H}(x, y)$ and $I_{2L}(x, y)$, $I_{2H}(x, y)$, respectively. Vertically filtering and down-sampling is then done using the low-pass and high-pass filters to each column of $I_{1L}(x, y)$, $I_{1H}(x, y)$ and $I_{2L}(x, y)$, $I_{2H}(x, y)$ to produce four wavelet pyramids or coefficient maps $I_{1LL}(x, y)$, $I_{1LH}(x, y)$, $I_{1HL}(x, y)$ and $I_{1HH}(x, y)$ for one level of decomposition of the first image $I_1(x, y)$ and $I_{2LL}(x, y)$, $I_{2LH}(x, y)$, $I_{2HL}(x, y)$ and $I_{2HH}(x, y)$ for one level of decomposition of the second image $I_2(x, y)$.

The fused wavelet coefficient map is then constructed from the above wavelet coefficients of the source images after five levels of decomposition, according to the fusion decision map that has been generated from a set of fusion rules. We used the averaging method as the rule for fusing the wavelet coefficients of the source images, due to its stabilization nature in fusion results. Finally, the fused wavelet coefficient map is inverse wavelet transformed to obtain the fused image. The overall process can be mathematically described by

$$I(x,y) = \S^{-1}(\partial(\S(I_1(x,y)), \S(I_2(x,y)))) \tag{6}$$

where the wavelet transforms § of two input images $I_1(x, y)$ and $I_2(x, y)$ are fused using the fusion rule ∂. The fusion rule ∂ used here is the average of the wavelet coefficients. The inverse wavelet transform $\S^{-1}$ is then computed to produce the fused image $I(x, y)$. The whole process of fusion has been pictorially explained in Fig. 1.

3. Fused image-based WaveMACH filter

A distortion-invariant filter is basically a linear combination of preprocessed training images and the preprocessing emphasizes high frequencies in an attempt to produce a delta function correlation peak. The MACH filter [15,16] is designed to maximize the relative height of the average correlation peak with respect to the expected distortions by maximizing a performance metric called the average similarity measure (ASM). The MACH filter f is thus given by [17]

$$f = S^{-1}M \tag{7}$$

where S is a diagonal matrix, called ASM, and is defined as

$$S = \frac{1}{N}\sum_{i=1}^{N}(X_i - M)(X_i - M)^* \tag{8}$$

M is the average of X_i and X_i are the Fourier transformed in-plane rotated training images generated from the fused image I of Eq. (6). The symbol * is used to indicate complex conjugate. The smaller the value of the ASM, the more invariant the response of the filter.

The WaveMACH filter uses a two-dimensional Mexican-hat wavelet function given by

$$h(x,y) = [1 - (x^2 + y^2)] \exp\left(-\frac{x^2 + y^2}{2}\right) \tag{9}$$