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An independent component analysis-based filter design for defect detection in low-contrast surface images

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Abstract

In this paper, we propose a convolution filtering scheme for detecting small defects in low-contrast uniform surface images and, especially, focus on the applications for backlight panels and glass substrates found in liquid crystal display (LCD) manufacturing. A defect embedded in a low-contrast surface image shows no distinct intensity from its surrounding region, and even worse, the sensed image may present uneven brightness on the surface. All these make the defect detection in low-contrast surface images extremely difficult.

In this study, a constrained independent component analysis (ICA) model is proposed to design an optimal filter with the objective that the convolution filter will generate the most representative source intensity of the background surface without noise. The prior constraint incorporated in the ICA model confines the source values of all training image patches of a defect-free image within a small interval of control limits. In the inspection process, the same control parameter used in the constraint is also applied to set up the thresholds that make impulse responses of all pixels in faultless regions within the control limits, and those in defective regions outside the control limits. A stochastic evolutionary computation algorithm, particle swarm optimization (PSO), is applied to solve for the constrained ICA model. Experimental results have shown that the proposed method can effectively detect small defects in low-contrast backlight panels and LCD glass substrate images.

Keywords: Defect detection; Surface inspection; Independent component analysis; Convolution filter; Particle swarm optimization

1. Introduction

Image analysis techniques are being increasingly used to automate industrial inspection. The manual activity of inspection could be subjective and highly dependent on the experience of human personnel. Subtle defects appearing in a low-contrast surface cannot be visibly identified even with a well-trained inspector. In automatic surface inspection, small defects which appear as local anomalies embedded in a homogeneous surface must be reliably detected. This paper considers the issue of designing a convolution filter for defect detection in low-contrast surface images using independent component analysis (ICA).

Defect detection in uniform surface images arises in glass plate [1], sheet steel [2], aluminum strips [3] and web materials [4]. Most of the existing defect detection methods for uniform surfaces use simple thresholding or edge detection techniques. Defects in these images can be easily detected because they commonly have distinctly measured values with respect to those of the uniform background. The inspection task in the present paper is the detection of subtle defects in uniform surfaces that involve low-contrast intensities in images. This type of surfaces arises in many industrial materials. In this paper, we especially aim at backlight panels and glass substrates in thin film transistor-liquid crystal display (TFT-LCD) manufacturing.

In recent years, there is a great demand for flat-panel displays used as monitors for notebook and personal computers, and as viewfinders for handheld devices such as cellular phones and PDAs. TFT-LCDs have become increasingly

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important as one of flat-panel display devices due to their full-color display capabilities, low power consumption and light weight. The backlight unit and LCD glass substrate are two important components composing a TFT-LCD module. The inspection of defects in such panel surfaces ensures the display quality and improves the yield in LCD manufacturing. Most of the existing machine vision algorithms for defect inspection in LCD panel surfaces are still mainly based on thresholding, edge detection and first-order statistics [5] such as mean and variance from the gray-level histogram of an image. Kim et al. [6] presented an automated inspection algorithm for detecting spot-type defects in TFT-LCD panels. An adaptive multi-level thresholding method that uses the statistical characteristics of the local area is applied for adaptive segmentation of spot-type defects. Saitoh [7] proposed a machine vision system for the inspection of LCD brightness unevenness. An edge detection algorithm was first used to detect discontinuous points. A genetic algorithm was then applied to extract the visual continuous boundary of a non-uniform brightness region for distinguishing true defects from noise. Jiang et al. [8] used a luminance meter, instead of a CCD camera, as the sensing device for detecting brightness unevenness in LCD panels. Analysis of variance (ANOVA) and exponentially weighted moving average techniques were applied to determine the presence of region-type defects. Sokolov and Treskunov [9] developed an automatic vision system for final output checks of LCDs. Their method was mainly based on the brightness distribution of an LCD image. It compares the average brightness of background between a reference LCD image and an inspection image to detect the appearance of defects.

In low-contrast surfaces, a local anomaly has smooth change of brightness from its surrounding region and, therefore, has no clear edges to apply the gradient-based methods for defect detection. The non-uniform intensity of a faultless region and the low-contrast intensity of a defective region also deter the use of simple thresholding methods. It is extremely difficult to reliably identify real defects in low-contrast surface images without false detection of noise. Lee and Yoo [10] proposed a complicated data fitting approach for detecting regional defects of brightness unevenness. They first estimated the background surface of an inspection image using a low-order polynomial data fitting. Subtraction of the estimated background surface from the original image is then applied to find the threshold for binary segmentation. The resulting image is then post-processed by median filtering, morphological closing and opening to remove noise and refine the segmentation. The proposed method worked successfully to detect regional defects in low-contrast TFT-LCD surface images. However, it is very computationally intensive because the background surface must be estimated recursively by eliminating one pixel at a time throughout the entire inspection image.

In this paper, we propose a convolution filtering scheme for defect detection in low-contrast uniform surface images. The design of the convolution filter is based on ICA with the goal that the resulting impulse responses are consistently the same for pixels in faultless regions and distinctly different for pixels in defective regions. ICA is a novel statistical signal process technique to extract independent sources given only observed data that are mixtures of the unknown sources, without any prior knowledge of the mixing mechanisms [11,12]. The observed signals are generally assumed to be a linear mixture of the unknown sources from a mixing matrix which is solved by maximizing the independency of the estimated source signals. The estimated source signals are termed independent components (ICs), and the inverse of the mixing matrix is called de-mixing matrix.

ICA has been widely applied in medical signal processing such as EEG, fMRI and MEG data [13–17], and audio signal processing [18,19] for the purpose of signal de-noising and extraction of meaningful sources for interpretation. It also has been applied in face recognition [20–23] and texture analysis [24–26] that used either the estimated ICs or the corresponding column vectors of the mixing matrix (or row vectors of the de-mixing matrix) as features for classification. Hyvarinen et al. [27,28], Hyvarinen [29] and Hung and Luo [30] used ICA for image de-noising. They applied the ICA algorithm and maximum a posteriori (MAP) estimator in a noise-free training image to find the mixing matrix. The mixing matrix is then used in a sensed image to obtain the noisy ICs. The shrinkage nonlinearity function is applied to remove noise in the noisy ICs. The filtered ICs were finally multiplied with the mixing matrix to restore the image.

In this study, ICA is used to design an optimal filter in the sense that the filter will generate the most representative source intensity of the background surface without noise so that all pixels in faultless regions have approximately the same impulse responses, while the pixels in defective regions have distinct responses in the filtered image. In an ICA model, ICs and the mixing matrix that constructs the observed signals can be estimated from the training samples by maximizing the independency of the estimated sources. Since any training image patches of the same size as the filter in a faultless surface image can be treated as translated versions of the same pattern, only one source is needed to be estimated in this study. The corresponding row vector of the estimated source in the de-mixing matrix is used as the convolution filter for defect detection in low-contrast uniform surface images.

An ICA model with a prior constraint is applied to determine the filter so that the impulse responses of all training image patches are as consistent as possible. The constraint incorporated in the ICA model is given by the upper and lower control limits defined by the mean and standard deviation of the resulting impulse responses of all image patches used in training. In this study, we propose a stochastic optimization procedure based on the particle swarm optimization (PSO) algorithm to effectively determine the de-mixing row vector, i.e. the convolution filter, of the constrained ICA model. In the inspection process, the same parameter value of the control limits used as the constraint in the training