Defect Inspection of Liquid-Crystal-Display (LCD) Panels in Repetitive Pattern Images Using 2D Fourier Image Reconstruction

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***Abstract*—Flat-panel displays have become increasingly important in recent years for use in handheld devices and video monitors. In this paper, we have considered the problem of detecting micro defects including pinholes, particles and scratches in patterned Thin Film Transistor-Liquid Crystal Display (TFT-LCD) surfaces. The proposed method is based on a global image reconstruction scheme using the Fourier transform. A typical TFT-LCD panel consists of orthogonal gate lines and data lines with TFTs in each intersection of the lines, which result in a structural texture with repetitive patterns. By eliminating the frequency components associated with the structural pattern of data lines, gate lines and TFTs, and back-transforming the Fourier domain image, the reconstructed image can effectively remove the background pattern and distinctly preserve anomalies. A simple adaptive thresholding is then used to segment the defective regions from the uniform background in the filtered image. Experimental results have shown that the proposed method can successively detect and locate various ill-defined defects in a TFT-LCD panel without designing and measuring the quantitative features of individual defect types**.

Keywords-defect detection; automated visual inspection; TFT-LCD; fourier transform

I. INTRODUCTION

Liquid crystal displays (LCDs) using thin film transistor (TFT) arrays are very important display devices used in smart phones, video monitors and televisions. In order to improve the display quality of LCD panels and increase the yield, the inspection of defects in the TFT-LCD panels becomes a critical task in the LCD manufacturing process.

Surface defects of a TFT-LCD panel not only cause visual failure but also cause electrical failure to operate the panel. Appearance defects in a TFT-LCD panel can be roughly classified into two categories: macro and micro defects. Macro defects include “MURA”, “SIMI” and “ZURE”. MURA means unevenness of color on a TFT-LCD panel. SIMI means stains on a panel, and ZURE means misalignment of a panel. Micro defects include pinholes, particles and scratches (see Figures 7(b1)-(d1) for the sample images). The macro defects appear as high contrast regions with irregular sizes and shapes. They are generally large in size and, therefore, can be detected by human inspectors. However, micro defects are generally very small in size, and cannot be easily found by human personnel or detected with electrical methods. In this paper, we propose a global Fourier reconstruction scheme that especially focuses on the detection of micro defects by utilizing the repetitively structural pattern of TFT-LCD panels.

A. *Related work*

There are several electrical and optical based inspection techniques available for TFT-LCD defect inspection [1]–[3]. The voltage-imaging technique measures the characteristics of a TFT-LCD array by directly measuring the actual voltage distribution on the TFT pixels. The main disadvantage of such approaches is that the probes used for voltage measurement must be separately designed for each panel configuration.

A number of vision-based techniques were developed for LCD defect inspection. Song et al. [4] developed a wavelet-based method to detect the MURA defects in low-resolution LCD images that involve non-textured surfaces. Lu and Tsai [5] applied the Independent Component Analysis (ICA) to detect defects in patterned LCDs. It can effectively detect local defects, but cannot extract the exact shape of a detected defect. Liu et al. [6] also studied the TFT-LCD inspection problem. It used the Locally Linear Embedding (LLE) to extract image features, and then applied the Support Vector Machine (SVM) for classification. The LLE must be carried out in each pixel defined in a small window and is time-consuming to calculate. The SVM requires a training process, and could be sensitive to environment changes. Kim et al. [7] used adaptive multi-level defect detection and probability density estimation for TFT-LCD inspection. It mainly focuses on MURA defects in non-textured surfaces. Lin et al. [8] presented an image processing method for defect detection in TFT-LCD images, where the inspection surface contains only simple data lines and gate lines. The genetic algorithm (GA) heuristic algorithm is applied to adjust the inspection function parameters. Gan and Zhao [9] used the active contour for defect inspection of LCDs. It aims at the MURA defects in non-textured image surfaces of the LCD. The active contour is generally very computationally intensive, and cannot be used for small defect detection in complicated pattern surfaces. Ngo et al. [10] also presented an automatic detection method for MURA defects. The method is based on an accurate reconstruction of the background by training the background from a set of test

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images. The existing vision-based techniques generally need a pre-stored reference image for comparison. This approach requires precise environmental controls such as alignment and lighting for the TFT-LCD panel under inspection. In our previous work [11], we proposed a Fourier-based method for defect detection in directional textures. It works successively for the LCD panels in a low resolution image that shows no TFT patterns. It fails to detect small defects in the LCD surfaces that present data lines, gate lines and TFTs.

B. Overview of the proposed method

In the LCD manufacturing process, perpendicular data and gate conductive lines are patterned onto the glass substrate. A thin film transistor is located at each intersection of the data and gate lines. Figure 1 demonstrates the magnified image of a TFT-LCD panel under the resolution of 120 pixels/mm. It comprises repetitive, horizontal gate lines and vertical data lines, in which the small black rectangular component at each intersection of lines is the TFT. Since the geometrical structure of a TFT-LCD panel surface involves repetitive, equally-spaced horizontal and vertical lines, it can be classified as a structural texture with oriented line pattern. The structural pattern of a TFT-LCD panel results in a homogeneously textured image that consists of an arrangement primarily of horizontal and vertical lines appearing periodically on the surface. The problem of defect detection in TFT-LCD panel surfaces can now be considered as a texture analysis problem in image processing.

The proposed method does not rely on conventional methods of textural feature extraction. It is based on a global image reconstruction scheme using the Fourier transform. The Fourier spectrum is ideally suited for describing the directionality of periodical line patterns in an image. The proposed Fourier-based image reconstruction scheme fully utilizes the structural characteristics of TFT-LCD panels by setting the frequency components that are associated with the repetitive, orthogonal lines and TFTs of a TFT-LCD panel image to zero, and back-transforming the Fourier domain image. The Fourier reconstruction process will then remove all background texture of the TFT-LCD panel surface, and distinctly preserve local anomalies in the filtered image. This converts the difficult defect detection in a complicated textured-image to a simple thresholding in a uniform image. The statistical process control is then used to set up the control limits (i.e., thresholds) for distinguishing between defective regions and faultless regions in the reconstructed image.

This paper is organized as follows: Section II first discusses the Fourier transform and the properties of repetitive TFT-LCD pattern in the Fourier plane. The removal of repetitive line and TFT patterns in the TFT-LCD panel is then described. Section III presents the experimental results from a number of TFT-LCD panel surfaces that contain faultless regions and micro-defects of pinholes, particles and scratches. The paper is concluded in Section IV.

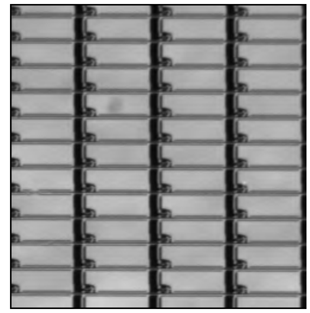

Figure 1. The image of a TFT-LCD panel under the fine resolution of 120 pixels/mm.

II. FOURIER IMAGE RECONSTRUCTION

In this paper, we use machine vision to solve the problem of defect detection in TFT-LCD panels. The Fourier-based image reconstruction technique is used to remove repetitively structural patterns in TFT-LCD surfaces.

Let $f(x, y)$ be the gray level at coordinates (x, y) in the spatial domain image of size $N \times N$. The discrete two-dimensional Fourier transform of $f(x, y)$ is given by

$$F(u,v) = \sum_x \sum_y f(x,y) \cdot \exp[-j2\pi(ux+vy)/N] \tag{1}$$

for frequency variables $u, v = 0,1,2,..., N-1$. The spectrum $F(u,v)$ is then centered. The Fourier transform is generally complex. That is, $F(u,v) = R(u,v) + jI(u,v)$, where $R(u,v)$ and $I(u,v)$ are the real and imaginary parts of $f(x, y)$, i.e.

$$R(u,v) = \sum_x \sum_y f(x,y) \cdot \cos[2\pi(ux+vy)/N] \tag{2}$$

$$I(u,v) = \sum_x \sum_y f(x,y) \cdot \sin[2\pi(ux+vy)/N] \tag{3}$$

The power spectrum $P(u,v)$ of $F(x, y)$ is defined by

$$P(u,v) = |F(u,v)|^2 = R^2(u,v) + I^2(u,v) \quad (4)$$

A. Removal of data and gate lines

A typical TFT-LCD panel consists of horizontal gate lines on one plane, and vertical data lines on the other plane. It results in an image of structural texture that contains orthogonal lines. Figures 2(a) and 3(a) show two TFT-LCD sample images: one is a faultless surface, and the other contains a pinhole defect. Figures 2(b) and 3(b) present the power spectra of the respective TFT-LCD surface images as an intensity function, where the brightness is proportional to the magnitude of the power spectrum $P(u,v)$. Note that the transform of periodical data and gate lines in the spatial domain image results in high-energy frequency components distributed along the horizontal and vertical lines passing through the center in the Fourier plane. Compared to the Fourier spectrum of the associated faultless TFT-LCD sample image, Figure 3(b) reveals that the pinhole defect has significant contribution to the frequency components around the center of the Fourier plane.

In order to remove the orthogonal data and gate lines in a TFT-LCD surface image, we can edit the Fourier domain image and set the associated high-energy frequency components to zero, and then apply the inverse Fourier transform to reconstruct the image. Let Δw denote by the notch width that determines the neighborhood regions for high-energy frequency components along both the horizontal line and vertical line in the Fourier plane. The high-energy frequency components associated with the orthogonal data and gate lines in the TFT-LCD plane are set to zero as follows:

Delete the frequency components within the horizontal notch of width Δw, i.e.

$$F(u,v) = 0 \text{ for all u's, and } v = 0, \pm 1, \pm 2, ..., \pm [\Delta w / 2]$$

so that the repetitive data lines in the spatial domain image can be removed. Also, delete the frequency components within the vertical notch of width Δw, i.e.

$$F(u,v) = 0 \text{ for all } v\text{'s, and } u = 0, \pm 1, \pm 2, ..., \pm [\Delta w/2]$$

so that the repetitive gate lines can be removed. With the newly assigned values of $F(u,v)$, the reconstructed image can be obtained using the discrete inverse Fourier transform. That is

$$\hat{f}(x,y) = \frac{1}{N^2}\sum_u \sum_v F(u,v) \cdot \exp[\, j2\pi(ux+vy)/N] \quad (5)$$

Figures 2(c) and 3(c) present, respectively, the reconstructed images of Figures 2(a) and 3(a) using the notch width Δw of 1 pixel, i.e., $F(u,0) = 0$ and $F(0,v) = 0$ for all u's and v's. The results show that the orthogonal data and gate lines in both faultless and defective TFT-LCD sample images are basically removed, and the pinhole defect is well preserved in the filter image. However, residuals distributed periodically along the vertical direction remain in both reconstructed images of the faultless and the defective TFT-LCD panel surfaces. The residuals in the filtered image are the result of the patterned TFTs that locate at each intersection of the data and gate lines.

B. Removal of TFTs

Given the Fourier spectrum of any complicated gray-level image, the frequency components circularly around the center of the Fourier plane are low frequency bands that represent the coarse approximation of the original gray-level image, and those apart from the center are high frequency bands that represent the details of the original image. As seen in Figure 3(b), the local anomaly embedded in a homogeneous texture contributes the frequency components around the center of the Fourier plane. The details of the homogeneous background texture are spread in the high frequency zone in the Fourier plane.

By applying the band reject filtering that deletes all frequency components outside the circle of a specific radius, the details of TFTs in the original gray-level image can be removed. As the filter radius increases, more details will be preserved in the reconstructed image. We can sufficiently remove all background texture of TFT-LCD panels and distinctly preserve anomalies in the filtered image by simultaneously deleting all frequency components on the horizontal and vertical lines passing through the center and those outside the circle of a given radius r^* in the Fourier plane, i.e.

$$F(u,0) = 0, \forall u;\ F(0,v) = 0, \forall v;\ \text{and}$$

$$F(u,v) = 0 \text{ for all } (u^2 + v^2)^{1/2} > r^* \quad (6)$$

The discrete inverse Fourier transform in eq. (5) is then applied to reconstruct the image.

Figures 4(b) and 5(b) show the Fourier spectra of the two TFT-LCD test samples in Figures 2(a) an 3(a), in which the black regions represent the frequency components with a set value of zero, i.e., $F(u,v)=0$. The selected filter radius r^* for TFT removal is 30 pixels for both test samples. The results in Figures 4(c) and 5(c) show that the reconstructed image of the faultless TFT-LCD panel surface in Figure 2(a) becomes a uniform white image, and that of the defective surface in Figure 3(a) contains only the pinhole defect.

Finally, we use the simple statistical process control limit to set up the threshold for distinguishing defects from the uniform background in the reconstructed image. The upper and lower control limits for intensity variation in the filtered image are given by $\mu_{\hat{f}} \pm \mathcal{K}\sigma_{\hat{f}}$, where $\mu_{\hat{f}}$ and $\sigma_{\hat{f}}$ are the mean and standard deviation of gray values in the whole reconstructed image. $\mathcal{K}$ is a control constant, which is generally in the range between 2 and 5.

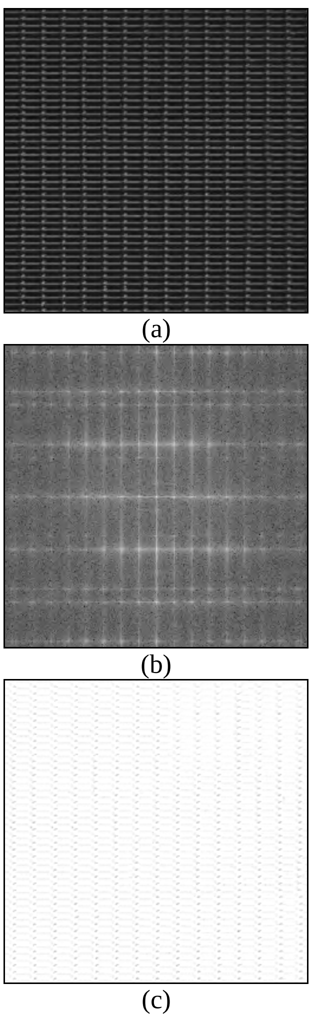

Figure 2. (a) A faultless TFT-LCD surface; (b) the corresponding Fourier power spectrum; (c) the reconstructed image by setting $F(u,0)=0$ and $F(0,v)=0$.

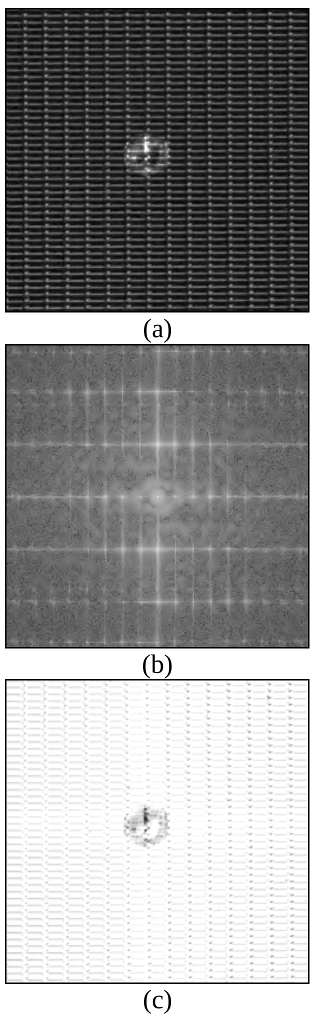

Figure 3. (a) A defective TFT-LCD surface with a pinhole; (b) the corresponding Fourier power spectrum; (c) the reconstructed image by setting $F(u,0)=0$ and $F(0,v)=0$.

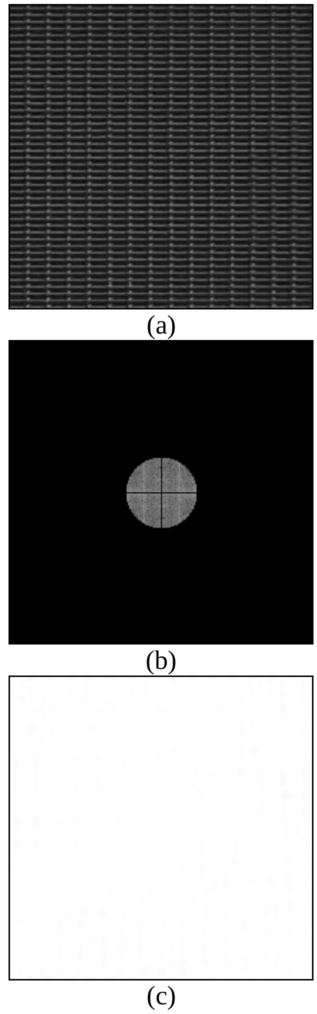

Figure 4. (a) The same faultless TFT- LCD sample shown in Figure 2(a); (b) the corresponding power spectrum, in which the black regions represent $F(u,v)$ with a set value of zero; (c) the reconstructed image from (b).

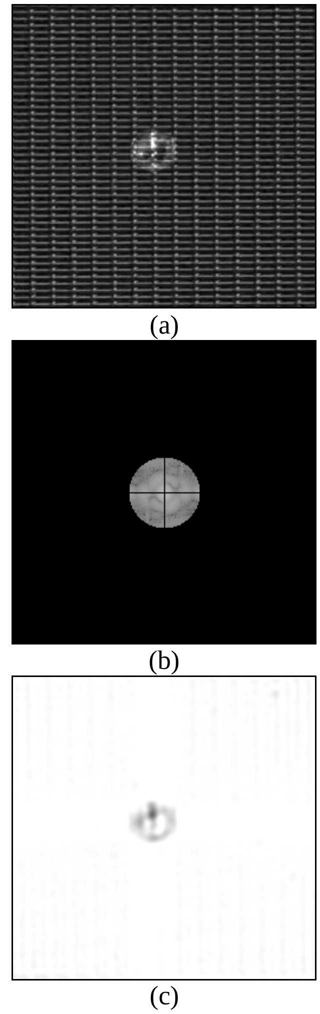

Figure 5. (a) The same defective TFT- LCD sample shown in Figure 3(a); (b) the corresponding power spectrum, in which the black regions represent $F(u,v)$ with a set value of zero; (c) the reconstructed image from (b).

III. EXPERIMENTS AND DISCUSSION

In this section, we present experimental results from a variety of micro defects including pinholes, particles and scratches in TFT-LCD panel surfaces to evaluate the efficacy of the proposed Fourier reconstruction scheme. Figure 6 shows the schema of the proposed automated visual inspection system, and the scan trajectory of the camera of a large LCD panel. The camera and light source are straightly on the top of the TFT-LCD panel. Two green bar-shaped LED lights are used for the illumination. The proposed Fourier-based method is fast enough to process the inspection while the camera is moving around the LCD panel. The test images are 256×256 pixels wide with 8-bit gray levels. Figure 7(a1)-(d1) shows respectively four images that involve a faultless surface, and three defective surfaces of pinhole, particle and scratch under the image resolution of 60 pixels/mm. These three micro defects can only be detected in images of a fine resolution, and cannot be reliably observed in images with a resolution below 50 pixels/mm.

The proposed method does not require defect-free TFT-LCD images for reference, and is tolerable to environmental changes, such as shifting and lighting. The notch width Δw used for eliminating the frequency components associated with orthogonal data and gate lines is 1 pixel for all test images. Throughout a preliminary experiment, a radius r^* of 30 pixels is used for all test samples in the detection of pinholes, particles and scratches. A large control constant $\mathcal{K}$ of 5 is used in this study for the final segmentation in the reconstructed image.

Figures 7(a2) through (d2) show the reconstructed results of the four test images in Figure 7(a1)-(d1), respectively. Figures 7(a3)-(d3) present the defect detection results of the reconstructed images, where pixels with gray values falling outside the control limits are marked in black, and the ones falling within the control limits appear in white. The results reveal that the resulting image of the faultless TFT-LCD surface is uniformly white, and the defects in all three defective surfaces are correctly segmented in the binary images. The suspect defects (i.e., the black points in the binary image) are further classified by evaluating the sizes (for particles and pinholes) and lengths (for scratches, using the Hough transform to accumulate the pixels on a line) in the binary image. An additional experiment that involves 100 defect-free test samples and 63 defective test samples is also conducted. The experimental results show all defective samples including particles, pinholes and scratches can be identified without false alarms if the defect sizes are larger than 5×5 pixels. The proposed method can detect a defect as small as 0.17 mm in physical size. The processing time of Fourier transform and inverse Fourier transform is around 0.1 seconds for an image of size 256×256 on a typical personal computer.

IV. CONCLUSIONS

In this paper, we have considered the problem of detecting micro defects embedded in TFT-LCD patterned surfaces. The proposed method is based on a global image reconstruction scheme using the Fourier transform. The merit of the proposed method is that it can be used to detect various ill-defined defects in a TFT-LCD panel without designing and measuring the quantitative features of individual defect types, and requires no template for the comparison.

The method proposed in this paper can be considered as a supervised one since the proper notch width Δw and filter radius r^* must be predetermined. It can be selected according to the structural pattern of a TFT-LCD panel under a given image resolution. The proposed method in this study mainly focuses on the detection of micro defects. It can be extended to the inspection of non-structured anomalies, such as MURA, or fingerprint in a low-resolution image of the patterned TFT-LCD panel.

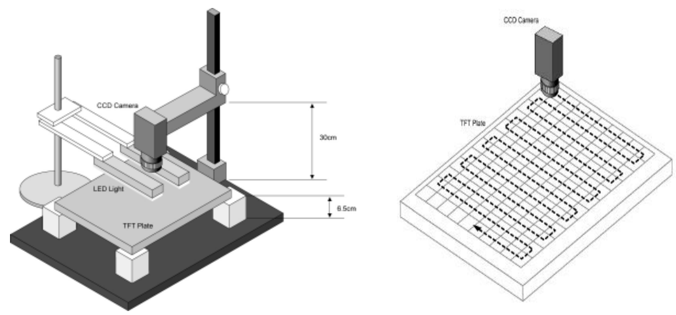

Figure 6. The configuration of the automated LCD inspection system, and the scan trajectory of the camera.

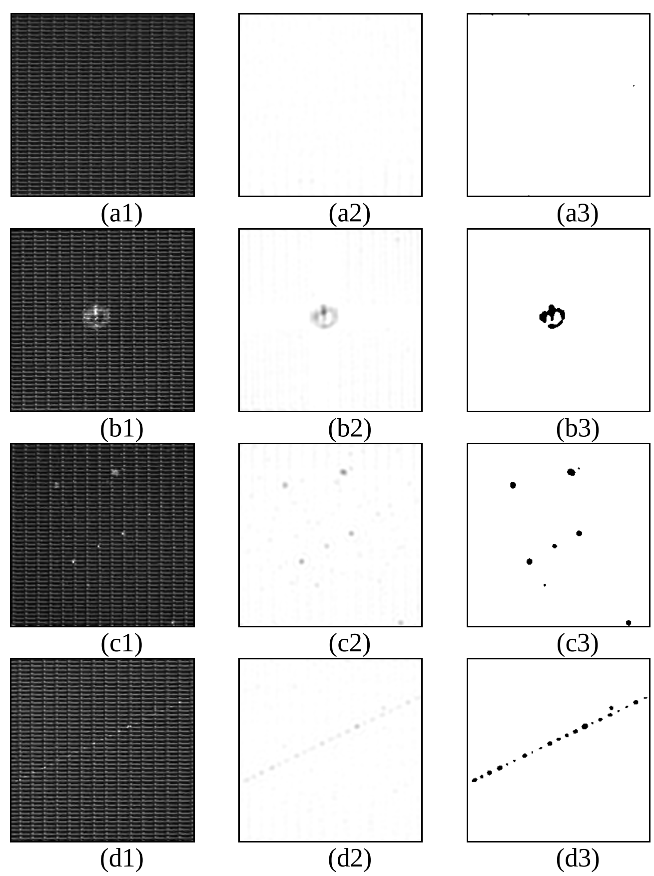

Figure 7. Four TFT-LCD panel images used for test: (a1) a faultless TFT-LCD surface; (b1)-(d1) defective TFT-LCD surfaces with respective pinhole, particle and scratch defects; (a2)-(d2) reconstructed images; (a3)-(d3) resulting binary images.

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