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## Multiple Images Viewable on Twisted-Nematic Mode Liquid-Crystal Displays

**Chai Wah Wu, Gerhard R. Thompson, Steven L. Wright**
IBM Research Division
Thomas J. Watson Research Center
P.O. Box 218
Yorktown Heights, NY 10598

# Multiple images viewable on twisted-nematic mode liquid-crystal displays

Chai Wah Wu, Gerhard Thompson, and Steven L. Wright

IBM Research Division, Thomas J. Watson Research Center
P. O. Box 218, Yorktown Heights, NY 10598, U.S.A.

**Abstract**

The twisted-nematic mode LCD display used in most laptop computers has the property that the luminance and color change dramatically as the viewing angle changes. The present letter utilizes this property to embed several images into the LCD display which are viewable depending on the viewing angle.

## I. Introduction

The twisted-nematic (TN) mode liquid crystal display (LCD) used in most laptop computers or digital cameras has the property that the luminance and color of the pixels change dramatically as the viewing angle changes. In fact, there is severe contrast reversal, so that images at a large off-axis viewing angle look like negative images. In this letter, we present a digital halftoning based method to exploit this property to embed two or more images (or video) into the LCD display such that each image is viewable at a different viewing angle. As an example, we construct in Section III a hybrid image which when displayed on a TN mode LCD display will look like one image when viewed at one angle and looks like another image when viewed at another angle. In this case, we say that two images have been *embedded* into the hybrid image.

## II. Embedding images

Let us first consider the case of grayscale images where we want to embed two images at two different viewing angles, as the general case is similar. Each pixel can be set to a (8-bit) grayscale value $g$. The perceived graylevel $p$ depends on the viewing angle in the vertical direction $\theta$. Thus we can write the perceived graylevel of a pixel with value $g$ as $p(\theta, g)$. Let the viewing angles be $\theta_1$ and $\theta_2$. For each input grayscale value $g$ there corresponds a pair of perceived graylevels $(p(\theta_1, g), p(\theta_2, g))$. Given an image $I = \{g_{ij}\}$ represented as a matrix of grayscale values $g_{ij}$, the images perceived under angles $\theta_1$ and $\theta_2$ are therefore $P_1 = \{p(\theta_1, g_{ij})\}$ and $P_2 = \{p(\theta_2, g_{ij})\}$ respectively. The goal is to make the images $P_1$ and $P_2$ look like the two intended images (denoted as $M_1$ and $M_2$). To accomplish this, we utilize digital halftoning techniques in the extended space of Cartesian product of pixel spaces [1]. A similar approach has also been used in embedding images for data hiding and multimedia authentication purposes [2].

In a digital halftoning algorithm [3], [4], an input image in an image space is approximated by a halftone image, where each pixel in the halftone image is taken from a restricted set of output colors in this image space. In our case, the image space is the extended space of Cartesian products of pixel spaces. For instance, in our case of embedding two grayscale images, the extended space consists of pairs of grayscale pixels. The pairs $(p(\theta_1, g), p(\theta_2, g)), g \in G$ from a selected set of grayscale values $G$ form the output colors in this extended space. The input image to the halftoning algorithm is a matrix of pairs of pixels, one from each image we want to embed.

In particular, when vector error diffusion [5] is used as the halftoning method, the algorithm for embedding images is shown in pseudocode form in Figure 1. The weights $w_u$ are the weights of the error diffusion filter and $\tilde{M}_u$ is the modified input of the $u$-th image $M_u$ respectively. $v_u$ are weighting factors to determine the fidelity of the embedded image. For instance, if $P_1$ should look very close to $M_1$, then $v_1$ should be large. The halftone image $Y$ when displayed on a LCD display would appear as different images depending on the viewing angle. The value of $q$ determines the norm that is used and is usually set at $q = 2$.

For each $i$ /* For each row */
 For each $j$ /* For each column */
  For $u \in \{1, 2\}$ /* For each image */
   $\tilde{M}_u(i,j) = M_u(i,j) + \sum_{x,y} w_u(x,y) e_u(i-x, j-y)$
  Endfor
  $Y(i,j) = \underset{g \in G}{\operatorname{argmin}} \sum_u v_u \|\tilde{M}_u(k,l) - p(\theta_u, g)\|^q$
   /* $p(\theta_u, g)$ is the perceived color at of a pixel with graylevel $g$ at angle $\theta_u$ */
  $(e_1(i,j), e_2(i,j)) = (\tilde{M}_1(i,j), \tilde{M}_2(i,j)) - (p(\theta_1, Y(i,j)), p(\theta_2, Y(i,j)))$
 Endfor
Endfor
The halftone image $Y$ is the embedded image.

Fig. 1. Pseudocode of image embedding algorithm using vector error diffusion.

## III. Example

As described in [4], [2], the halftoning is more effective if the convex hull of the output colors covers the gamut in the image space and the set of output colors is spread over the gamut in the image space uniformly. In our case, the image space consists of pairs of integers in the range $(0, 255)$, which span a square in $R^2$. Based on measurements of the luminance of the pixels at different viewing angles, we choose 4 pairs (i.e., $G$ has 4 elements) as the set of output colors. A plot of these pairs and their convex hull is shown in Fig. 2. The convex hull does not quite cover the image space completely. To avoid large errors, we reduce the gamut by projecting the image space into the convex hull. By using these output colors, we have constructed an image which when displayed on a LCD screen appears as either a rose (Fig. 3a) or as an infant (Fig. 3b) depending on the viewing angle.

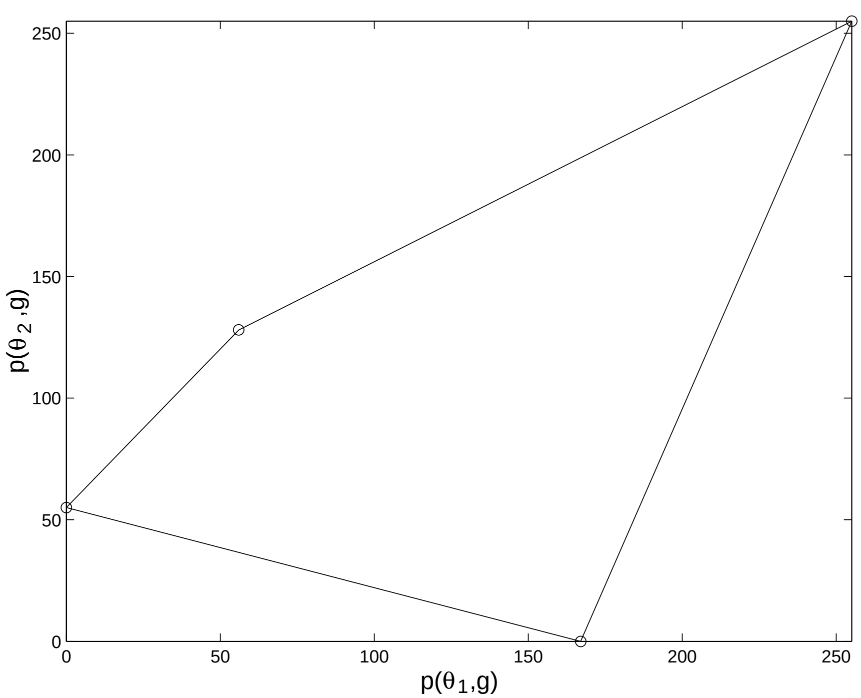


Fig. 2. Plot of output color pairs $\{p(\theta_1, g), p(\theta_2, g)\}_{g \in G}$ and their convex hull.

(a)

(b)

Fig. 3. (a) Image viewed from LCD display at angle $\theta_0$. (b) Same image viewed from LCD display at angle $\theta_1$.

## IV. Conclusions

We have presented a method to construct an image such that when viewed on a TN-mode LCD display at different angles, appears as different images. By embedding the same image into different viewing angles, this method can be used to improve the range of viewing angles of TN-mode LCD displays. For another method to improve the viewing angle characteristics of TN-mode LCD displays, see [6]. When the observer is close to the LCD display, the subtended visual angle is relatively large and the viewing angle of a pixel with respect to the observer's eyes depends on the pixel location, especially in the vertical direction. This dependence can be incorporated into the definition of the perceived graylevel $p(\theta, g, i, j)$ and in the error diffusion algorithm. The case of color images can be handled by splitting the image into appropriate channels or by applying vector error diffusion in the Cartesian product of the color spaces (such as RGB or LAB). Extension to video is possible by processing individual frames or by using spatio-temporal halftoning to process the video stream as a whole. By using grayscale values whose perceived graylevels do not change much with respect to viewing angle variations, we can improve the robustness of the embedded images with respect to viewing angle perturbations in order to maximize the "sweet spot" where the observer can be located to view the displayed image.

## References


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