

PRODUCING AUTOMATED MOSAIC ART IMAGES OF HIGH QUALITY WITH RESTRICTED AND LIMITED COLOR PALETTES

Tefen Lin and Jie Wang

Department of Computer Science, University of Massachusetts, Lowell, MA 01854, U.S.A.

Keywords: Error diffusion, Floyd-Steinberg dither, Serpentine Floyd-Steinberg, Block error diffusion, Sub-block error diffusion.

Abstract: In mosaic art images made from bricks, tiles, or counted cross-stitch patterns, artists would need to divide the original image into small parts of reasonable sizes and shapes and represent the colors of each part using just one “closest” color selected from a given color palette. Using standard methods to automate this process, the resulting mosaic image may contain undesirable visual artifacts of patches and color bandings. Error-diffusion dithering algorithms have been used to reduce such artifacts. We observe that image parsing directions are critical for diffusing errors, and we present a new error-diffusion scheme called “Four-Way Block dithering” (FWB) to correct certain artifacts caused by existing methods, including the directional and latticed appearance produced by Floyd and Steinberg’s dithering (FSD). FWB divides the input image into blocks of equal size with each block consisting of four sub-blocks such that the size of each sub-block is suitable for an underlying error-diffusion algorithm. Scanning the blocks from left to right and from top to bottom, for each block being scanned, FWB starts from the center of the block and diffuses errors along four directions on each sub-block. We show that FWB can better retain the original structure and reduce unstructured artifacts. We also show that FWB dithering produces much better peak signal-to-noise ratios on mosaic images over those generated by FSD.

1 INTRODUCTION

Photographic images are used widely in digital forms. Uploading self portraits or other images to blogs, for example, has become a common practice. As an application of digitized images, we have worked with brick and tile companies during the past several years to develop a web-based system that creates automated mosaic art images with small pieces of colored tiles or bricks. Based on current technology, tile manufacturers can only produce tiles of limited colors. In particular, the tile manufacturers we have worked with can typically produce 48 different colors on square tiles of small size, which can be as small as $\frac{1}{2}$ cm \times $\frac{1}{2}$ cm. These 48 colors form our color palette (see Figure 1). We chose to work on 1 cm \times 1 cm square tiles for the purpose of reducing manufacturing cost and easing the labor on assembling the pieces together. We also need to resize the original image to fit in standard picture frames. A typical picture frame is 50 cm wide with its height determined by the width/height ratio of the original image.

Our process can be described as follows: We first resize the original image of size $w \times h$ pixels to the desired size of w' pixels wide and $w'h/w$ pixels high, where w represents width and h represents height. For example, the original image of da Vinci’s painting of Mona Lisa (the portion of the head) is 136×182 pixels. We resize it by retrieving its own embedded thumbnail and scale it to the size 50×64 pixels (see Figure 2 (a)). If the image does not contain an embedded thumbnail image, we create a thumbnail image to size 50×64 pixels by scaling the main image. This resized image is referred to as the input image. Most of the colors in the input image may be unavailable in the given color palette.



Figure 1: The color palette available for tiles.

Next, for each pixel in the input image, we calculate the Euclidean distance from its RGB value to the RGB value of each of the 48 available colors in the color palette (note that each RGB value may be viewed as a 3-dimensional vector), and select a color with the smallest Euclidean distance. If there is more than one color with the same smallest distance, we select one from these colors with the smallest Euclidean distance from their HSB (Hue, Saturation, and Brightness) values to the HSB value of the pixel. Figure 2 (b) shows the result of this process.

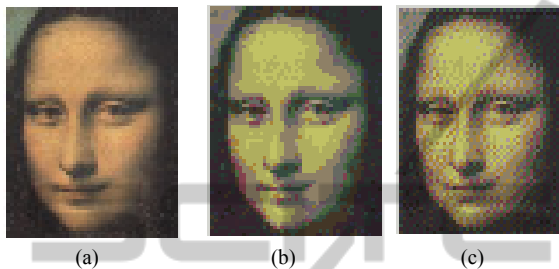


Figure 2: Size of these images: 50 pixels wide and 67 pixels high. (a) Input image. (b) The image with reduced color using the limited color palette. (c) The image produced by Floyd-Steinberg dither .

This process is likely to yield color bandings and patches that produce dramatically different visual effect from the input image (as shown in Figure 2 (b)) because of color reduction. To enhance the visual quality of the image, we need to find ways to conceal or minimize these artifacts. This process is referred to as color quantization.

Dithering is a useful technique to transform an image of continuous tone to an image of limited given colors. A number of dithering algorithms have been devised during the past three decades, including threshold dithering, random dithering, pattern dithering, and error-diffusion dithering. Error diffusion dithering intends to diffuse the quantization error of a given pixel to its neighboring pixels. Published in 1975, Floyd and Steinberg's error diffusion dithering algorithm (Floyd and Steinberg, 1975), referred to as FSD, has been the most popular dithering algorithm. It uses a set of values of $1/16$, $5/16$, $3/16$, and $7/16$ to diffuse a pixel's error to its lower left, lower, lower right, and right neighbors, respectively, producing a dithering image shown in Figure 2 (c).

Listed below are a number of other error-diffusion methods.

Coefficient error diffusion dithering. Jarvis, Judice, and Nink (Judice and Ninke, 1976) devised a dithering algorithm using a much more complex

error diffusion coefficient matrix than the one used in FSD. Shiao and Fan's dithering algorithms (Shiao and Fan, 1993), Stucki's dithering algorithm (Stucki, 1981), Burkes' dithering algorithm (Daniel Burkes, 1988), and Atkinson's dithering algorithm (Atkinson, 2003) all use different sets of error diffusion coefficient matrices.

Changing image parsing direction. Dithering is often carried out by scanning a pixel one at a time, from left to right and from top to bottom. Other parsing directions may be applied. For example, one may parse an image following a serpentine path using the FSD error diffusion coefficient matrix, instead of parsing it line by line or with a space-filling curve (Riemersma, 1998).

Variable coefficients error diffusion. Ostromoukhov (Ostromoukhov, 2001) proposes to use variable error diffusion coefficient matrix based on the input image.

Block error diffusion and sub-block error diffusion. Both algorithms parse image four pixels at a time, which were proposed by Damera-Venkata and Evans (Damera-Venkata and Evans, 2001), respectively. The sub-block error diffusion improves block error diffusion, using four 2×2 error diffusion matrices for pixels contained in one block.

Reported in (Caca Labs., 2010), the serpentine dithering, block dithering, and sub-block dithering tend to produce poorer image quality than FSD. Hocevar and Niger (Hocevar and Niger, 2008) confirmed that the original FSD coefficients were indeed amongst the best possible for raster scan. However, as observed by others and confirmed by our studies, FSD still contains a number of drawbacks. For example, FSD tends to produce noticeable visually distributing artifacts in highlight and dark areas. More ever, on certain intensity levels close to $1/2$, $1/3$, $2/3$, $1/4$, and $3/4$, patches of regular structure are likely to appear. Uneven transitions between "structure" and unstructured" areas may be clearly visible (Ostromoukhov, 2001). For example, as shown in Figure 2 (c), Mona Lisa's right eye displays a serious defect—it is much narrower than that shown in Figure 2 (a) and (b), which makes the right eye look like half closed.

FSD parses an image in raster scan. Observed by Hocevar and Niger (Hocevar and Niger, 2008) and confirmed by our experiments, errors in FSD tend to propagate to the lower-left direction of each pixel or to the lower-right direction. Thus, the output image may look tilted. We observe from a large number of imaging experiments that the image parsing direction is crucial in error diffusion. This is probably due to the fact that, once a pixel completely diffuses

quantization error to its neighbors, only one direction of the quantization error would be nicely diffused, but not the errors in other directions. This effect seriously affects the image quality and causes the output image to appear directional and latticed. For example, Figure 3 produced by FSD clearly depicts the vertical directions and lattice appearance. More explanations why this could happen will be presented in Section 3.



Figure 3: An image produced by FSD clearly depicts vertical directions and lattice appearance. Size of the output image: 50 pixels wide and 47 pixels high.

To retain the original image structure and resolve the directional and latticed appearance, we devise a new error diffusion scheme called Four-Way Block (FWB) diffusion. FWB divides the input image into blocks of equal size with each block consisting of four sub-blocks such that the size of each sub-block is suitable for an underlying error-diffusion algorithm. For example, when we use FSD, the size of sub-blocks may be set to $3k$ pixels wide and $2k$ pixels high for the same positive integer k . Scanning blocks from left to right and from top to bottom, for each block being scanned, FWB starts from the center of the block and diffuses errors along four directions on each sub-block. This process has the effect of diffusing errors backward. This is different from the existing error-diffusion dithering methods that always move and diffuse errors forward in the direction it parses the image. This mechanism helps to diffuse errors without leaving a visible trace of error propagation. We show that FWB can improve the quality of mosaic images. In particular, we show that FWB produces much better peak signal-to-noise ratios (PSNR) on mosaic images over those generated by FSD.

The rest of the paper is organized as follows. In Section 2 we will briefly describe the FSD algorithm. We present our new FWB error-diffusion scheme in Section 3 and provide detailed dissemination. In Section 4 we provide running comparisons of FSD and FWB using FSD as the underlying error-diffusion algorithm. We conclude the paper in

Section 5. In Appendix we provide a number of examples of mosaic art images.

2 FLOYD-STEINBERG ERROR DIFFUSION DITHERING

FSD is widely used in dithering images of continuous tone. The quantization error, which is the difference between the color in the input image and the closest color in the limited color palette, will be distributed to its four neighboring pixels by the coefficient error diffusion matrix shown in (1). FSD scans the original image from left to right and from top to bottom as shown in Figure 4.

$$1/16 * \begin{bmatrix} 0 & 0 & 0 \\ 0 & x & 7 \\ 1 & 5 & 3 \end{bmatrix} \quad (1)$$

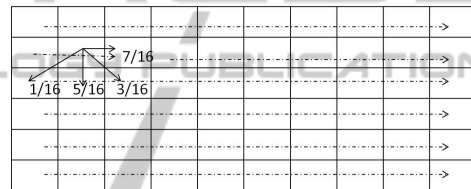


Figure 4: Floyd-Steinberg dithering scans an image file from top to bottom and from left to right one pixel at a time. Each cell in the Figure represents one pixel.

3 FWB, A NEW SCHEME FOR ERROR DIFFUSION

How to reduce artifacts caused by FSD is a central issue in generating automated mosaic art images. We devise FWB based on the following three observations.

1. FSD has a simple parsing mechanism based on a nice error-diffusion coefficient matrix. Other error-diffusion algorithms may also work nicely for certain type of images.
2. The image parsing direction is crucial in error diffusion.
3. The existing error diffusion algorithms only diffuse errors in a forward direction. We note that making diffusion backward may help diffuse errors better.

The FWB error-diffusion scheme follows the following four steps:

1. Choose an underlying error-diffusion algorithm (FSD, for example).
2. Divide a given input image to blocks of equal size with each block consisting of four sub-blocks of equal size (except the bottom and right-hand edges) suitable for the underlying error-diffusion algorithm. For example, when FSD is chosen, we may set the sub-block size to be $3k$ pixels wide and $2k$ pixels height for some positive integer k .
3. Scan the blocks from left-to-right and from top to bottom. For each block being scanned, apply the underlying error-diffusion algorithm in four directions on each sub-block starting from the center point of the block. If a block is already parsed, then it does not allow its neighboring blocks to rewrite its values.
4. Use both Euclidean distances of RGB and HSV values to select the closest color from the given color palette for the output pixel.

Note that FWB may not be able to divide a given image evenly, that is, if we divide the image starting from the upper-left pixel, then, we may not be able to obtain full blocks at the bottom or at the right-hand side. When this happens, we will just apply the underlying error-diffusion algorithm on these blocks in the usual manner. This is a small price to pay, and the majority of the pixels will receive better error diffusion.

Denote by FWB-XYZ the FWB scheme with XYZ being the name of the underlying error-diffusion algorithm.

3.1 Block Size

The size of the block is crucial for achieving a good image quality. Based on our experiments, FWB-FSD produces the best image quality when $k = 1$. That is, the size of each sub-block is 3×2 pixels. Unless otherwise stated, we assume that the default block size is 6×4 pixels.

In the next section we will use other block sizes to show that the best block size is 6×4 pixels for FWB-FSD. In this section, we will use the sub block size 6×4 pixels to explain FWB-FSD.

3.2 Sub-block Parsing Directions

To prevent the latticed and directional appearance in the output image and keep the structure of the input image, we observed that the parsing order is critical. We have explored a number of different parsing orders and discovered that under a given parsing

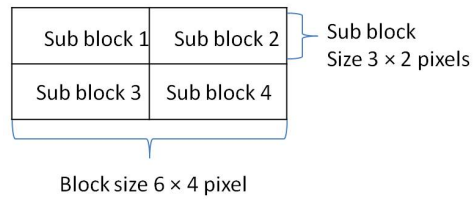


Figure 5: An input image divided into blocks, where each block consists of 4 sub-blocks of equal size, except the bottom and the right-hand edges.

order, color bandings of different input images would tend to appear in the same direction. For example, Figure 6 (a) and (c) are output images obtained from two different vertical parsing directions: top-down in (a) and bottom-up in (c). These two output images both depict vertical directional artifact color bandings. Figure 5 (b) is an output image obtained from a horizontal parsing of right to left. It depicts a horizontal directional artifact color banding.

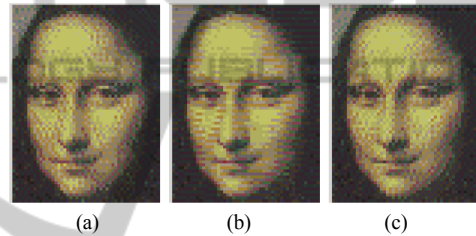


Figure 6: Observable directional artifacts: (a) and (c) are output images from vertical parsing, while (b) is an output image from a horizontal parsing.

In the FWB error-diffusion scheme each sub-block in a block is parsed in a different direction. Sub-block 1 in Figure 5 is parsed bottom-up and from right to left using FWB-FSD. Sub-block 2 is parsed top-down and from left to right. Sub-block 3 is parsed top-down and from right to left. Sub-block 4 is parsed top-down and from left to right. The directions between sub-blocks have the effect of asteroid emission, which prevents double compensation on one pixel and keeps 4 pixels in each block from being diffused by other pixels (see Figure 7). This helps to remain the structure of the input image.

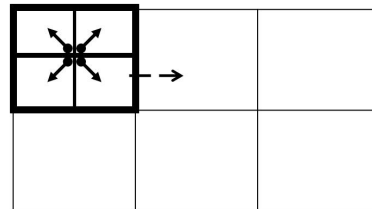


Figure 7: For each block being scanned, FWB parses each sub-block in a different direction.

3.3 The Euclidean Distance for Selecting the Best Color for a Pixel

We want to select the closest color from the given color palette to that of the original input pixel. Early research has indicated that perceived differences between colors are well represented by the Euclidean distance of the RGB vectors. The color models can be presented by RGB, MYK, CIEXYZ, CIELAB, HSB and YIQ.

The application is based on the Microsoft window. RGB is a device dependent color space of Microsoft window. HSB is that it often used by artists because it is often more natural to think about a color in terms of hue and saturation than in terms of additive or subtractive color components. HSB is a transformation of an RGB color space, and its components and colorimetric are relative to the RGB color space from which it was derived.

We use the RGB color space and the HSB values to represent colors. A particular RGB color space is defined by the three chromaticities of red, green, and blue. HSB stands for Hue, Saturation, and Brightness, which is one of the most common cylindrical-coordinate representations of points in an RGB color model. HSB rearranges the geometry of RGB that is more perceptually relevant than the Cartesian representation. We calculate the closest color using both RGB and HSB values: We first calculate the Euclidean distance of RGB value for each pair of a given input color and a color in the given set of limited color palette. Select the color with the smallest distance. If there are two or more such pairs with the same Euclidean distance, we will compute the Euclidean distance on the HSB values on these pairs, and select the one with the smallest distance.

In particular, we use c to represent the value in RGB space. Let $c = (c_r, c_g, c_b)$ be the RGB vector of a pixel in the input image and $X = \{(x_{i_r}, x_{i_g}, x_{i_b}) \mid i = 0, \dots, n - 1\}$ be the given set of colors in the color palette.

We want to find the shortest Euclidean distance d .

$$\min\{d \mid d = \sqrt{(c_r - x_{i_r})^2 + (c_g - x_{i_g})^2 + (c_b - x_{i_b})^2}\} \quad (2)$$

where $(x_{i_r}, x_{i_g}, x_{i_b})$ is one of the colors in X , $i = 0, \dots, n - 1$.

If there are two or more colors in X with the same shortest distance to c , we will calculate the shortest Euclidean distance of the HSB values of these colors to the HSB value of c and select the color with the shortest Euclidean distance of HSB values. Since the Hue value is much larger, we will first normalize it (dividing it by 360) to a value between 0 and 1 before

calculating the Euclidean distance.

We may also use rectilinear distance to find the "closest" color. Shown in Figure 8 are two output images, where Figure 8 (a) is obtained by finding the first shortest rectilinear distance difference of the RGB vectors of c and the colors in X . Figure 8 (b) is created by finding the shortest Euclidean distances of both the RGB space and HSB values, which incur lesser color bandings and result in a smoother image than Figure 8 (a).

Figure 9 shows two examples of color selection mechanism used in FWB-FSD. The first row indicates an input color of RGB space and HSB in the coordinates x and y . In each of these two examples there are two colors in the second and third rows with the same shortest Euclidean distance of the RGB vector in the original image. The second row in Figure 9 is selected by the RGB space and has the same Euclidean distance with the third row. The third row in Figure 9 is selected by the HSB and has the same Euclidean distance with second row. With the help of HSB values, we are able to select the color that is closest to the original.

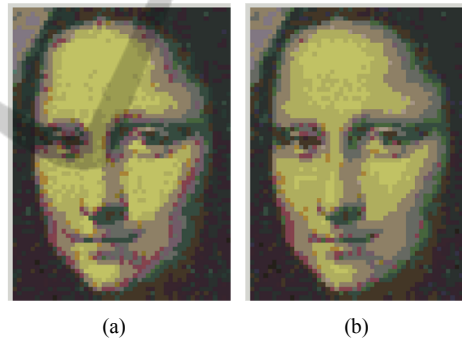


Figure 8: (a) Selecting colors by the shortest rectilinear distances difference of RGB vectors. (b) Selecting colors by the shortest Euclidean distances of RGB vectors and HSB values.

| X | Y | Distance | R | G | B | Color | Dis | Hue | Brightness | Saturation |
|----|---|----------|----|----|----|-------|-------|--------|------------|------------|
| 35 | 6 | | 57 | 59 | 69 | | | 230.00 | 0.25 | 0.10 |
| 35 | 6 | 21 | 52 | 49 | 70 | | 18.57 | 248.57 | 0.23 | 0.18 |
| 35 | 6 | 21 | 53 | 75 | 63 | | 82.73 | 147.27 | 0.25 | 0.17 |
| 35 | 6 | 21 | 52 | 49 | 70 | | 18.57 | 248.57 | 0.23 | 0.18 |

| X | Y | Distance | R | G | B | Color | Dis | Hue | Brightness | Saturation |
|----|---|----------|----|----|----|-------|--------|--------|------------|------------|
| 40 | 2 | | 47 | 52 | 52 | | | 180.00 | 0.19 | 0.05 |
| 40 | 2 | 13 | 67 | 54 | 38 | | 146.90 | 33.10 | 0.21 | 0.28 |
| 40 | 2 | 13 | 42 | 48 | 46 | | 20.00 | 160.00 | 0.18 | 0.07 |
| 40 | 2 | 13 | 42 | 48 | 46 | | 20.00 | 160.00 | 0.18 | 0.07 |

Figure 9: The column Dist is for distance of HSB, H for Hue, S for Saturation and B for Brightness. The color in the second row was selected without the HSB values comparison, while the color in the last row was selected in Fig. 8 (b), which is closer to the original color.

3.4 Error Diffusion in Blocks and Sub-blocks

FWB-FSD uses the FSD error-diffusion coefficient to parse pixels in each sub-block and distributes the quantization error to its neighboring pixels. After selecting the closest color, it diffuses the quantization error to its neighbors. How neighboring pixels will be compensated is determined by the locations of the parsing pixel of sub-block in the block (see Figure 10).

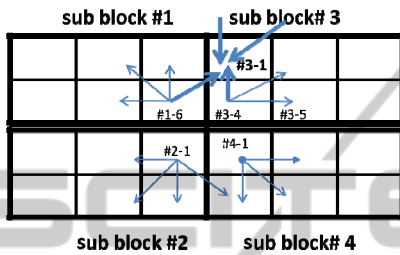


Figure 10: Under FWB-FSD the pixel number 3-1 gains the different portion of quantization error from different directions.

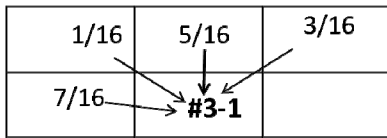


Figure 11: The pixel number 3-1 in FSD gets error diffusion from different quantization error of different pixels in only one direction.

The portions of quantization error are obtained differently between pixels depending on the locations of sub-blocks. We note that if a block is already parsed, then it will not be parsed by the unprocessed blocks again. For example, pixel #3-1 shown in Figure 10 receives 4 portions of error quantization including the two portions from the sub-block above, a portion from pixel #1-6, and a portion from pixel #3-4. Thus, the sequence of the portions it receives will be 5/16, 3/16, 3/16, and 3/16. Major differences between FWB-FSD and FSD are that pixel #3-1 in FWB-FSD receives error diffusions from more directions than FSD and the pixels #1-6, #3-4, #2-1 and #4-1 shown in Figure 10 keep the same RGB values without being compensated from other pixels. There are four cells in the sub block will not propagate its error-diffusion to its next neighbors. They are the last cell in the sub block 1 of the first block, the last cell in the sub block 2 of the last block of first row, the last cell in the sub block 3 of last row of the first block and the last cell in the sub block 4 of

the last row of the last block in the image which comparison with FSD that its last cell in the image. As the result, FWB-FSD not only better maintain the image quality without losing too much information of the input image but also reduce directional and latticed appearance in the output image. Figure 12 depicts the differences in the output images using these two methods. The difference is particularly noticeable in Mona Lisa's right eye: It is blurry in Figure 12 (a) under FSD, which looks like half closed. It is much clearer in Figure 12 (b) under FWB-FSD. We will provide more details in the next section.

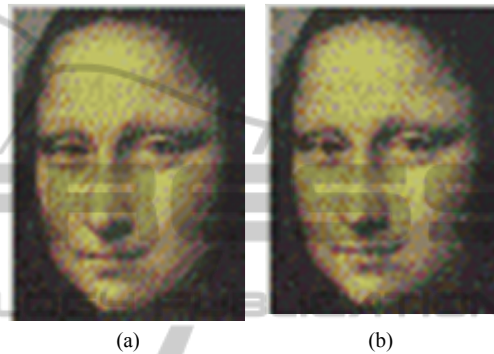


Figure 12: (a) Output image by FSD. It is clearly noticeable that Mona Lisa's right eye is blurry and looks half closed. (b) Output image by FWB-FSD. The eye problem in (a) is corrected.

3.5 Running Time

We note that FWB-FSD scans each pixel only once as in FSD. For each pixel it scans, FWD-FSD carries the same number of operations as FSD except that FWD-FSD may be in a different direction. Thus, the running time of FWD-FSD is the same as FSD. Likewise, it is easy to see that the running time of FWD-XYZ is the same as error-diffusion algorithm XYZ.

4 RESULT AND EVALUATION

Parsing direction plays a crucial role in error-diffusion dithering for achieving good quality and retaining detailed information of the input image. The direction to obtain good quality depends on the colors of the input image. Thus, using different directions to diffuse errors can enhance quality of the output image.

This section presents comparisons of more output images under FSD and FWB-FSD (see Figures. 13 to 15). We first use images of continuous tone and different shapes to compare the output images

produced FWB-FSD and FSD. For images of extremely simple shape (e.g. a rectangle) of one continuous simple color, we observe uneven structure in the output image produced by FWB-FSD (see Figure. 13). However, for images of simple shapes (such as rectangles, stars, and circles) with more colors, FWB-FSD produces much smoother images than FSD (see Figure 14). The orange square in the Figure 14 is smoother than left side image.

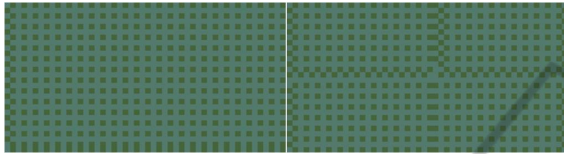


Figure 13: The left-side image is processed by FSD and the right-side image is processed by FWB-FSD with one block.



Figure 14: The left-side image is processed by FSD; the square of orange color shows an uneven structure. The right-side image is processed by FWB-FSD with one block; the square appears smoother.

We also used the peak signal-to-noise ratio (PSNR) to evaluate the final images processed with different block sizes. In particular, we will PSNR values to analyze the quality of the proposed method and evaluate the optical mixture correctness of the dithering process (Cheuk-Hong, Oscar, Ngai-Man, Chun-Hung and Ka-Yue, 2009).

When comparing input images, PSNR is often used as an approximation to human perception of reconstruction quality. The PSNR computes the ratio between two images. This ratio is often used as a quality measurement between the original and a reconstruction image. The higher PSNR has the better quality of the reconstructed image. Denote by $Y(i, j)$ the input image. The input image produced by FSD or FWB-FSD is denoted by $X(i, j)$. Denote by w the width of an image and h its height. The expression of PSNR is shown below:

$$MSE = \frac{1}{w \times h} \times \sum_{j=0}^{h-1} \sum_{i=0}^{w-1} [|Y(i, j) - X(i, j)|]^2$$

$$PSNR_{L,PF} = 10 \times \log_{10} \left(\frac{255^2}{MSE} \right)$$

Table 1 lists the results of PSNRs on the input image of Mona Lisa (50×67 pixels) and its output images produced by, respectively, FSD and FWB-FSD with a few reasonable block sizes. Table 2 lists the results of PSNRs on the original image of Mona Lisa (136×182 pixel) as the input image and its output images produced by, respectively, FSD, FWB-FSD with one block and FWB-FSD with block size of 6×4 pixels, where FWB-FSD with one block means to divide the image into four parts of equal size by connecting the middle points on each side of the image. We note that FWB-FSD with block size of 6×4 pixels produces the best PSNR. Additional comparisons are presented in the appendix.

Table 1: The results of PSNRs on the input image of Mona Lisa (50×67 pixels) and its output images.

| The algorithm to process | value |
|---|--------------|
| FSD | 22.42 |
| FWB-FSD with one block | 22.53 |
| FWB-FSD with block size 6×4 pixels | 22.64 |
| FWB-FSD with block size 12×8 pixel | 22.46 |
| FWB-FSD with block size 24×16 pixel | 22.46 |

Table 2: The results of PSNRs on the original image of Mona Lisa (136×182 pixel) as the input image and its output images.

| The Algorithm to Process | Value |
|---|--------------|
| FSD | 22.54 |
| FWB-FSD with one block | 22.68 |
| FWB-FSD with block size 6×4 pixels | 23.04 |

5 CONCLUSIONS

The output image generated by FSD tends to be rigid with directional and latticed appearance, which could lose the vividness of the original image. This is undesirable in an art product. The images generated by FWB-FSD have corrected these problems. We have demonstrated that our FWB error-diffusion scheme is a promising new method for achieving mosaic images of higher quality. We have tested a large number of other input images not presented here, and found that FWB-FSD with block size of 6×4 pixels always produces the best PSNR values compared to FSD and FWB-FSD with other block

sizes.

We note that for PSNR values below 3.00, it is often difficult for human eyes to detect differences between two images. But mosaic art images enlarge each pixel, and so it is easier to observe differences between two pictures with PSNR value below 3.00. We have shown that FWB-FSD is a better algorithm on mosaic art images and other types of images that require enlargement of pixels. In particular, we found that the FWB scheme works better when the input image has abundant colors and is rich in shapes.

Finally, we note that we can use other error-diffusion algorithms to go with the FWB scheme. For certain type of images, using a different underlying error-diffusion algorithm may be more appropriate than using FSD.

ACKNOWLEDGEMENTS

This work was supported in part by the NSF under grant CCF-0830314.

REFERENCES

Bayer, B., 1976, *Color imaging array*. U.S. patent 3,971,065.

R. Floyd and L. Steinberg, 1975. *An adaptive algorithm for spatial grey scale*, SID Intl. Svmp. Dig. Tech. Papers VI, 36–37.

F. Jarvis, C. N. Judice and W. H. Ninke, 1976, *A Survey of Techniques for the Display of Continuous Tone Pictures on Bi-level Displays*. Computer Graphics and Image Processing, 5 13–40.

Jeng-Nan Shiau and Zhigang Fan, 1993, *Method for Quantization Gray level Pixel data with extended distribution set*, United States Patent, Patent number 5,353,127.

P. Stucki, MECCA, 1981, *a multiple error correcting computation algorithm for bi-level image hard copy reproduction*. Research report RZ1060, IBM Research Laboratory, Zurich, Switzerland.

Daniel Burkes, 1988, *Presentation of the Burkes error filter for use in preparing continuous-tone images for presentation on bi-level devices*, in LIB 15 (Publications), CIS Graphics Support Forum.

Bill Atkinson, 2003, private correspondence with John Balestrieri, January

T. Riemersma, 1998, *A Balanced Dither Algorithm*, C/C++ Users Journal, volume 16, issue 12.

Victor Ostromoukhov, 2001, *A Simple and Efficient Error-Diffusion Algorithm*. In Proceedings of SIGGRAPH 2001, in ACM Computer Graphics, Annual Conference Series, pp. 567-572.

N. Damera-Venkata, B.L. Evans, 2001, *FM halftoning via block error diffusion*, proceedings of the 2001 International Conference on Image Processing, Caca Labs., 2010 <http://caca.zoy.org/>.

Sam Hocevar and Gary Niger, 2008. *Reinstating Floyd-Steinberg: Improved Metrics for Quality Assessment of Error Diffusion Algorithms*, ICISP 2008, LNCS 5099, PP. 38-45.

Cheuk-Hong Cheng, Oscar C. AU, Ngai-Man Cheung, Chun-Hung Liu, Ka-Yue YIP, 2009, *Low Color Bit-depth Image Enhancement by Contour-Region Dither*, Communications, Computers and Signal Processing, 2009, Page(s): 666 – 670. 2009

APPENDIX

DEMONSTRATION OF MOSAIC ART IMAGES

We present four examples of mosaic art images using FWB-FSD and compare them with the images generated by FSD (see Figure 15, 16, 17). The images shown in Figure 17 and 18 are the simulated mosaic art images while Figure 18 is the real mosaic art made by a total of 3,350 pieces of 1cm × 1cm tiles.

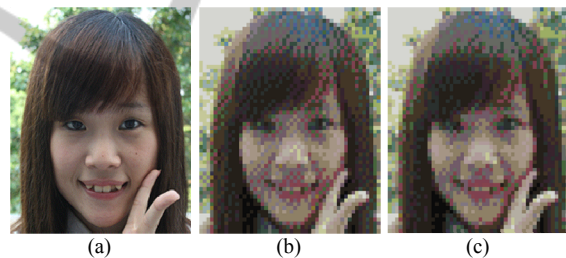


Figure 15: (a) The input image. (b) The output image with size 50 × 59 pixels generated by FSD. (c) The output image of the same size generated by FWB-FSD. Image (b) has the error quantization diffused to neighbor pixels that destroy the structure of the mouth. It has the latticed and unstructured look surrounding the mouth and cheeks. Image (c) is much better than Image (b) in all aspects.

Table 3: The results of PSNRs on the input image shown in Figure 16(b) and 16(c), both comparing the output image with the original image.

| The algorithm to process | Value |
|------------------------------------|-------|
| FSD | 24.14 |
| FWB-FSD with block size 6×4 pixels | 24.48 |

Table 4: The results of PSNRs on the input image shown in Figure 17(b) and 17(c), both comparing the output image with the original image.

| The algorithm to process | value |
|------------------------------------|-------|
| FSD | 24.13 |
| FWB-FSD with block size 6×4 pixels | 24.85 |

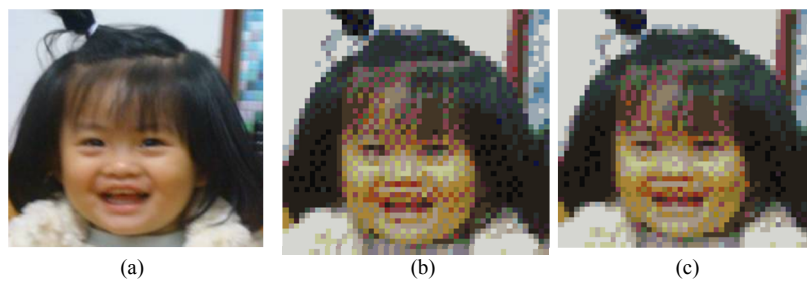


Figure 16: (a) The input image. (b) The output image with size 50×47 pixels generated by FSD. (c) The output image of the same size generated by FWB-FSD. Image (b) has unstructured cheeks that divide the face into two parts. Image (c) has corrected this problem.

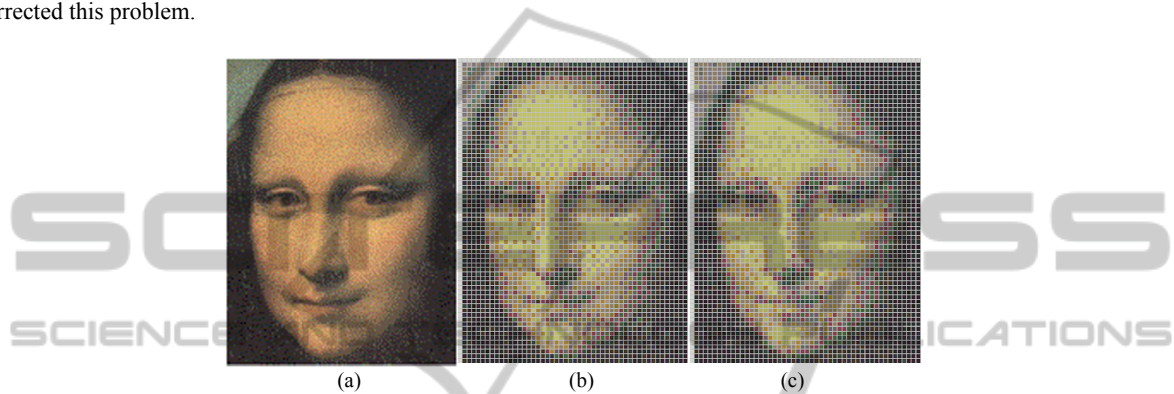


Figure 17: Mona Lisa images. (a) Input Image. (b) The output image which simulated mosaic art with 50×67 tiles generated by FSD. (c) The output image which simulated mosaic art with 50×67 tiles generated by FWB-FSD. Image (c) is clearly much better than Image (b).

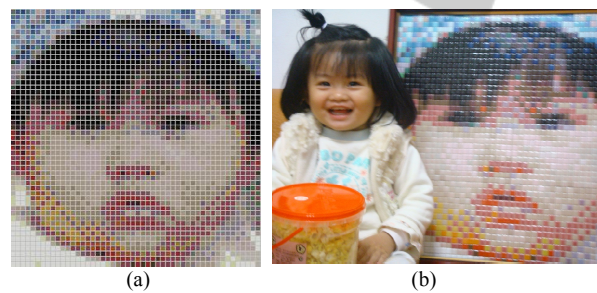


Figure 18: (a) The image which simulated mosaic art generated by FWB-FSD. (b) Mosaic Art with size 50×67 on $1 \text{ cm} \times 1 \text{ cm}$ square tiles.