Photo-inkjet Printing Method Based on the Limited Total Amount and Dot-visibility of Six-colorant

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Abstract

With the rapid growth of photo-inkjet printers using six-colorant in response to the spread of digital and mobile cameras, there has been a lot of research regarding six-color separation in order to achieve visually smooth tones in highlight regions. Most conventional method use the maximum amount of colorant with a low dot-visibility, thus resulting in paper wetness, poor edge-sharpness, and ink spreading and blotting in printed images. In order to reduce the amount of unnecessary colorants, this paper proposes a photo-inkjet printing method based on the limited total amount and dot-visibility ordering of a six-colorant. First, CIELAB values are estimated for an input CMY image using a color-mixing model, then these values are compared with the pre-calculated CIELAB values that correspond to all combinations of the CMYKlclm (Cyan, Magenta, Yellow, blacK, light cyan, and light magenta) colorants. This is done by using a color-difference constraint, which can determine the initial CMYKlclm candidates. Next, limitations on the total amount of colorant are imposed on the initial CMYKlclm candidates in order to remove excessive colorant, then the final CMYKlclm candidates are determined by minimizing the usage of light cyan and light magenta in the dark regions, based on a dot-visibility ordering of C, M, Y, K, lc, and lm. Finally, a lookup table is generated. It is composed of the CMY values versus the CMYlclm digital values. Experiments showed that the proposed method could effectively reduce the use of unnecessary colorants, while preserving good image quality.

Introduction

With portable cameras and LCD displays becoming increasingly popular, interest in photo-quality printing has also rapidly increased, thus resulting in the development of hi-fi printers with more than four colorants, such as CMYKOG (Cyan, Magenta, Yellow, blacK, Orange, and Green) and CMYKlclm [1]. CMYKOG printers are generally used in the textile industry to extend color gamut and reduce metamerism by adding extra colorants, i.e. orange and green with different hues from C, M, Y, and K [2]. Meanwhile, CMYKlclm printers focus on reproducing smooth tones in highlight regions by using light cyan and light magenta, which have the same hues as that of standard colorants, yet different concentrations. Moreover, the use of various concentrations can reduce coarse dot patterns and achieve greater resolution on various substrates, such as uncoated, copy, and photo papers. The CMYKlclm printers have gradually become a favorite of customers in the current market with regard to making inroad into film developing and printing. In high-fidelity printer with the N-primary colorants, the (N-3) degrees of freedom, equal to the number of extra colorants, makes it possible for reproducing the same tristimulus value by different combination of colorants amount, with changing the gamut shape and dot-visibility as an essential part of image quality. The degree of freedom raises the redundancy problem and thus a six-color separation method is first required to compute the amount of CMYKlclm colorants that correspond to the CMYK colorants when CMYKlclm colorants are printed on papers using digital halftones.

Traditional six-color separation using color-difference identifies monotonically increasing functions that convert M into (M, lm) and C into (C, lc), under the constraints of minimizing color-difference [3]. Although this method yields accurate colorimetric reproductions, the image quality is inferior due to the use of cyan or magenta that has high dot-visibility in bright regions. Hauang and Nystrom presented a method that produced a smooth tone and decreased abrupt differences in lightness between light and dark colors, color-differences, however, arose due to hue differences between diluted and saturated colorants [4]. As such, the six-color separation method using additional colorants and a quantitative granularity metric was also proposed by Son et al [5], where yellow and light magenta with a low dot-visibility were used as additional colorants based on a color-mixing rule in bright regions. As a result, differences in hue were corrected and the amount of graininess was reduced. Meanwhile, Agar proposed a model-based color separation method in order to reduce the amount of measurement data and to maximize the usage of colorants via an ordering of Y, lc, lm, C, M, and K [6]. Here, an accurate colorimetric reproduction and a smooth-dot pattern can be simultaneously achieved, yet excessive amounts of colorants are used due to the maximum usage of colorants with low dot-visibility. Such factors can result in paper wetness, an increase in dry time, and degradation of image quality due to poor edge-sharpness, ink spreading and blotting. Accordingly, in order to reduce the amount of unnecessary colorants, this paper proposes a photo-inkjet printing method based on the limited amount and dot-visibility ordering of a six-colorant. For an objective assessment, the CIE1976 color-difference metric, the total amount of color, and dot-visibility were evaluated. Regarding a subjective evaluation using real images, the resulting images were compared with other method.

Six-colorant Separation Based on Total-ink Limitation and Dot-visibility Ordering

A flowchart of the proposed method for reducing the amount of colorant used is shown in Fig. 1. First, CMY and CMYlclm digital values, that satisfy uniform data distribution in CIELAB space, are generated and printed using digital halftones. Their spectral reflectance is then estimated using the YNSN (Yule Nielsen Spectral Neugebauer) model in order to reduce the measurement data [7]. Next, the estimated spectral reflectance is multiplied with the relative daylight power distribution and a color-matching function to create CIELAB values. These values are compared by using the constraint of a color-difference less than that of a pre-defined threshold. This results in initial CMYlclm candidates corresponding to each CMY digital value. Thereafter, excessive amount of colorants are removed by imposing a limitation on the total amount of colorant for the initial CMYlclm candidates, then the final CMYlclm candidates are obtained by reducing the usage of lc and lm in dark regions, based on a dot-visibility ordering of C, M, Y, K, lc, and lm. Finally, a lookup table, composed of the CMY versus CMYlclm digital values, is constructed to simplify the complex computations of the six-color separation method.

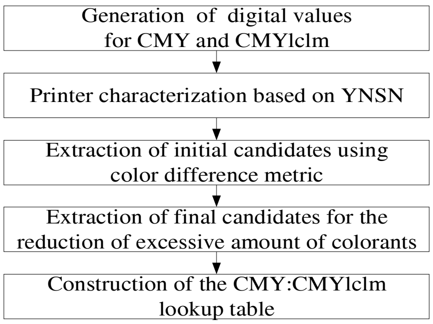

Figure 1. *The flowchart of the proposed six-color separation method*

Generation of Digital Values for CMY and CMYlclm

The CMY and CMYlclm digital values, stored in the lookup table for six-color separation, are generated by uniform and non-uniform sampling. Regarding calibrated CMY digital values using a linearization method, the combination of CMY digital values sampled based on an interval of $n = 51$ for each channel creates a uniform CIELAB value distribution, however, if the digital values for the CMYlclm colorants are generated using uniform sampling, the CIELAB values will congregate in dark regions, while the number of sample points in the bright regions is seriously deficient. Therefore, the digital values for the CMYlclm colorants are non-uniformly sampled based on an interval of $n = 11$ on average in bright regions with fine sampling and a $0 \sim 128$ range, and $n = 21$ in dark regions with a $129 \sim 255$ range.

Estimation of Spectral Reflectance Using Color Mixing Model

Depending on the printer, the CMY and CMYlclm digital values need to be converted into an independent color space for accurate color reproduction. Since increased amounts of colorants are used in hi-fi printers, an established model-based color mixing model, the YNSN model, is used to estimate the spectral reflectance of arbitrary printed patches based on the weighted average spectral reflectance of the Neugebauer primaries [7]. At the same time, it is important to consider the optical scattering into the substrate, which can be achieved by the following:

$$R(\lambda) = \left[\sum_{i=1}^{64} w_i R_i(\lambda)^{\frac{1}{n}} \right]^n \qquad (1)$$

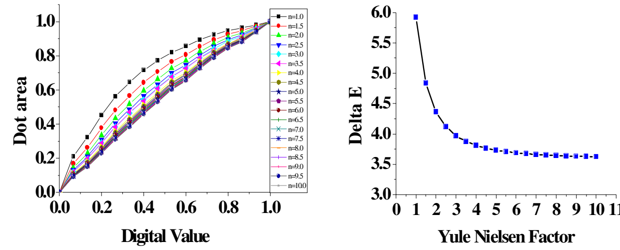

Figure 2. *(left) Estimated dot areas and (right) color-difference according to Yule-Nielsen factor n*

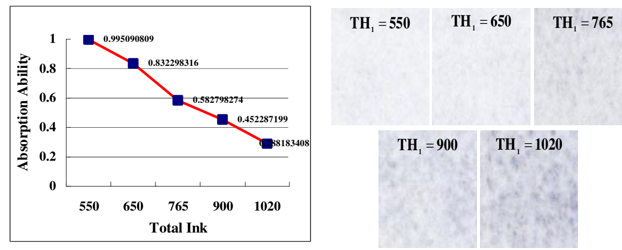

Figure 3. *Determining Total Colorant; (left) Absorption ability and (right) the reverse side of the paper*

where $R(\lambda)$ is the estimated spectral reflectance, w_i is the function of the digital value that indicates the relative dot area printed on the paper, and n is the optical scattering factor that accounts for the nonlinear relationship between the reflectance and the area coverage. To determine the dot area and optical scattering factor, w_i is optimized by using a spectral regression method for a fixed n. For example, the calculation of the cyan dot area is given by,

$$c_j = \frac{\sum_{\lambda \in V} [P_W(\lambda)^{\frac{1}{n}} - R(\lambda)^{\frac{1}{n}}_{c_j}][P_W(\lambda)^{\frac{1}{n}} - P_C(\lambda)^{\frac{1}{n}}]}{\sum_{\lambda \in V} [P_W(\lambda)^{\frac{1}{n}} - P_C(\lambda)^{\frac{1}{n}}]^2} \qquad (2)$$

where c_j is the dot area of the cyan colorant, j is the digital value that varies between 0 and 255, λ represents the wavelength between 400 nm to 700 nm, $P_w(\lambda)^{1/n}$ is the spectral reflectance of the paper, and $R(\lambda)^{1/n}_{cj}$ is the spectral reflectance of the cyan. First, the reflectance of the cyan ramp generated by uniform sampling and white paper are measured using a spectrophotometer, then Eq. (2) is substituted in order to create the optimal dot area that corresponds to each digital value in the cyan ramp. This is followed by linear interpolation. Thereafter, with a fixed w_i, the optimal n is determined by varying the parameter value n and comparing the color-difference with arbitrary color charts. Fig. 2(a) shows the estimated dot-area function, which decreases as the optical scattering factor increases, thus representing the reduction of the optical dot gain due to light penetration and scattering. Meanwhile, in Fig. 2(b), the color-difference converges to a constant value if the value of the optical scattering reaches approximately four, allowing the use of any value above four.

The Extraction of Initial Candidates Using Color – difference Metric

The estimated reflectance values of all CMY and CMYlclm colorants are transformed into CIELAB values, then the initial CMYlclm candidates are extracted by imposing a CIE1976 color-difference constraint, which keeps the color-difference within an acceptable tolerance when compared to the CIELAB values for the CMY input data. The CIE1976 color-difference is described by the Euclidean distance:

$$\Delta E_{ab}^{*} = \sqrt{\left(\Delta L^{*}\right)^{2} + \left(\Delta a^{*}\right)^{2} + \left(\Delta b^{*}\right)^{2}}$$
$$\Delta L^{*} = L_{s}^{*} - L_{c}^{*}, \Delta a^{*} = a_{s}^{*} - a_{c}^{*}, and\ \Delta b^{*} = b_{s}^{*} - b_{c}^{*} \quad (3)$$

where (L_s, a_s, b_s) represents the CIELAB values for the input CMY and (L_c, a_c, b_c) represents the CIELAB values for all CMYlclm candidates. The initial candidates for each CMY input are then extracted from all CMYlclm candidates using a color-difference constraint that is less than a predefined threshold value.

$$\Delta E_{ab}^{*} < TH_1 \quad (4)$$

where TH_1 is the threshold value of an acceptable color-difference between two color patches and the value is generally 6 , the present study, however, used $TH_1 = 5$, as the CMYlclm candidates are insufficient if the TH_1 value is less than 4.90 [8].

The Extraction of Final Candidates Based on Reducing the Amount of Excessive Colorant

The use of excessive colorant can cause image quality to deteriorate due to paper wetness, poor edge-sharpness, ink spreading and blotting. In addition, ink cartridges need to be changed more frequently, thus placing an economic burden on the customer. Therefore, a method to reduce the amount of colorants is needed, which is based on limiting the total amount of colorant and dot-visibility ordering for six-color separation. First, the maximum amount of ink is imposed on the initial CMYlclm candidates in order to reduce excessive amounts of colorant, irrespective of the type of colorant:

$$Total\ \ Colorant = C + M + Y + lc + lm < TH_2 \quad (5)$$

where *Total Colorant* indicates the sum of amount of the colorant needed for the initial CMYlclm candidates and TH_2 is the maximum amount of CMYlclm colorant allowed to represent colors that correspond to the input CMY. In order to determine TH_2 based on the absorption ability of the photo-inkjet paper, a spectrum image that includes all colors is printed using six-color separation while changing the total-ink limitation, i.e. the TH_2 value. Next, the reverse side of the photo-inkjet paper is scanned in order to calculate the average digital value and standard deviation that reflect the degree of ink penetration and blotting, respectively. As a result, the absorption ability of the photo-inkjet paper is calculated by multiplying the average digital value with the standard deviation.

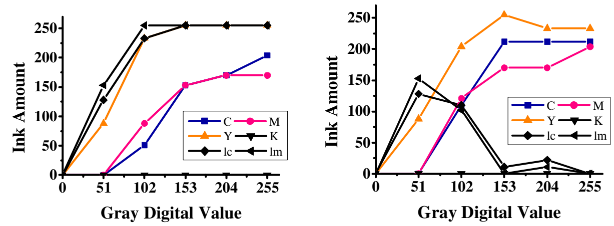

Figure 4. *Photo-ink separation passes for gray ramps; (left) Agar's method and (right) the proposed method.*

$$MEAN = \frac{1}{NM}\sum_{i=1}^{N}\sum_{j=1}^{M} g(i,j) \quad (6)$$

$$STD = \sqrt{\frac{\sum_{i=1}^{N}\sum_{j=1}^{M} g(i,j) - MEAN}{NM}} \quad (7)$$

$$Absorption\_ability = Nor(MEAN) \times Nor(\frac{1}{STD}) \quad (8)$$

where g indicates the digital value for the reverse side of the paper at a spatial coordinate (i, j), $MEAN$ and STD represent the average digital value and standard deviation for the reverse side of paper, respectively, and Nor is the normalizing function. In Fig. 3(a), when the value of TH_2 is more than 650, the absorption ability of the reverse side of the printer paper abruptly begins to decrease, indicating the absorption threshold value for the photo-ink paper. In addition, ink penetration generating blots on the reverse side of the printed paper, which are due to excessive amounts of colorants, can also be determined based on observation, as shown in Fig. 3(b). Figure 4 shows the photo-ink separation passes for gray ramps when using Agar's method and the proposed method [3]. A photo-ink separation pass represents the amount of CMYlclm-colorant when separated from the amount of CMY-colorant. The sum of the CMYlclm digital value is calculated for gray ramps in order to determine the appropriate amount of colorant needed and the proposed method can reduce the amount of colorant by 35% , as compared with Agar's method. In Agar's method, however, unnecessary amount of the lc and lm colorants can be used in the dark region due to the maximum use of lower visibility and an inapplicable case of total colorant limitation. Even though diluted colorants with lower visibility are used in the dark, graininess is not further reduced because the occupied dot area of the saturated colorants is very large [5]. Thus, the algorithm that is used to minimize the usage of the lc and lm in the dark region should be carefully considered in addition to the limitation of the amount of total colorant. Figure 5 shows a flowchart for minimizing the usage of lc and lm in dark regions with a different dot-visibility ordering according to the four types of regions that are classified with regard to the combination of C and M in the CMYlclm candidates. This is done after applying the limitations of the total amount of colorant. If C and M digital values are larger than the threshold values of $TH_c = 153$ and $TH_m = 102$, respectively, the starting point that determines the maximum usage of lc and lm, that is a bright region where the human eye is very sensitive to dot visibility. Thus, the final candidates that maximize colorants with a lower dot-visibility, Y, lc, lm, C, and M, which are evaluated by the lightness value [6], are extracted from the candidates based on limitation of the total-colorant. Meanwhile, if C digital value is less than TH_c and M digital value is more than TH_m, this region is classified as having a reddish color with a high saturation that does not require any improved dot-visibility. In other words, the use of lc, lm, and Y colorants is unnecessary under a guarantee of color-fidelity. In addition, in this type of region, the amount of lc should be less than that of lm, while the amount of M should be more than that of C in order to achieve better purity. Thus, a different dot-visibility ordering is applied to the candidates to minimize lm, lc, and Y and maximize M and C. For more green or cyan colors, where the C digital value is greater than TH_c and the M digital value is less than TH_m, the value of C should be larger than that of M to improve purity, while the digital value of lm should be smaller than that of lc to decrease meaningless visibility. Thus, dot-visibility ordering is defined to minimize lc, lm, and Y and maximize C and M. Finally, if C and M digital values are greater than each threshold value, a dark region ensues which is independent of the visibility ordering of lc and lm or C and M. Since the dot-visibility of the C colorant, however, is less than that of M, it is recommended that the amount of C should be more than that of M. Thus, in this type of region, dot-visibility ordering is directed to minimize lc, lm, and Y and maximize C and M. Figure 6 shows that the photo-ink separation passes when the proposed method is used for cyan and magenta ramps. The solid lines represent the amount of ink when using only the limitation of colorant, while the dotted lines represent the amount of ink when using dot-visibility ordering. After computing the amount of colorant for the cyan and magenta ramps, the constraints of dot-visibility ordering reduced the amount of colorant by 14% and 23%, respectively, when compared with only the constraint of the total amount of colorant.

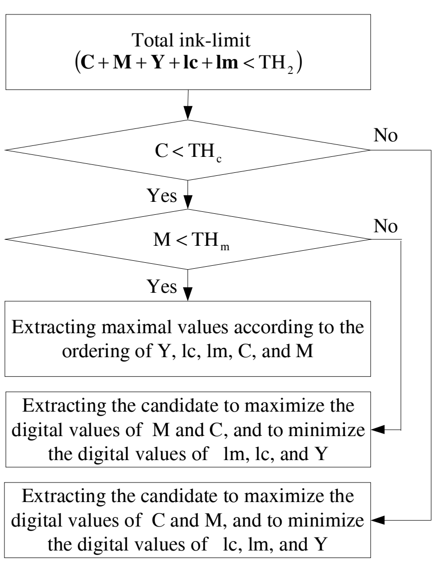

Figure 5. *Block-diagram for reducing the amount of lc and lm colorants*

Experimental Results

For the experiments, an EPSON STYLUS PHOTO 700 printer was used with a resolution of 360dpi. To print the input image, input RGB image was converted into the CIELAB values using forward monitor characterization such as GOG (Gain Offset Gamma) or S-curve model and then gamut mapping is applied for the CIELAB values to overcome gamut mismatch between the monitor and the printer [8]. Next, six-color separation method is conducted to determine the optimal combination of colorants corresponding to the gamut-mapped CIELAB values, with three constraints of color difference, dot-visibility, and total colorant amount [9]. Finally, the binary images of each channel are created by using the scalar error diffusion to diffuse the quantization errors into the neighborhood pixels [10].

Three quantitative metrics, including the CIE1976 color-difference, total-colorant amount, and dot visibility, were used to evaluate the proposed six-color separation for test sample patches. In Table 1, the color-difference metric was calculated using the CIE1976 color-difference equation and the total amount of colorant was the relative amount for the proposed method when the amount for Agar's method was regarded as 100%. Dot visibility was the sum of the standard deviation numbers of the lightness values in S-CIELAB space [5].

In Table 1, the color-difference between Agar's method and the proposed method can be regarded as equal, due to using the same color-difference constraint, as a color-difference of 0.21 cannot be detected by the human eye. With regard to the amount of colorant and visibility, however, although dot visibility with the proposed method was higher than that with Agar's method due to the maximum use of the lc, lm, and Y colorants, the total amount of colorant used by the proposed method was significantly reduced by 32% when compared with that of Agar's method. As a result, frequency in replacing ink cartridges was reduced and this relieved customers of further economic burden. Notwithstanding, a dot visibility of 3 does not have any influence on image quality. To demonstrate this, a subjective evaluation was conducted using real images; a 'house' and a 'room'. Figures 7(a) and 7(c) show the resulting images for a 'house' and Figs. 8(a) and 8(c) for a 'room', when using Agar's method and the proposed method, respectively. The corresponding cropped images are shown in Figs. 7(b), 7(d), 8(b), and 8(d). As such, Figs. 7 and 8 demonstrate that both methods reproduced a similar smooth dot pattern, however, the sharpness was more enhanced with the proposed method than with Agar's method. Furthermore, these results also showed that maximizing dot-visibility could produce a blurred image. For the reverse side of the printed images, as shown in Figs. 7(e), 7(f), 8(e), and 8(f), the proposed method effectively reduced ink penetration and blotting due to the excessive amount of colorant used.

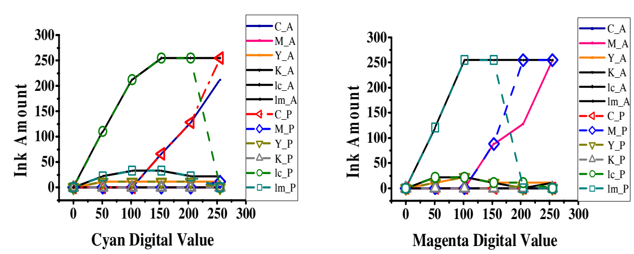

Figure 6. *Photo-ink separation passes using the proposed methods for cyan and magenta ramps; (left) Cyan ramp and (right) Magenta ramp*

Table 1. The quantitative evaluation of the proposed six-color separation method

Method	Color difference	Total colorant amount	Dot visibility
Agar's method	4.54	100	40.18
Proposed method	4.33	68	43.44

Conclusion

This paper proposed a photo-inkjet printing method based on limiting the total amount of ink and dot-visibility ordering in order to reduce the unnecessary use of colorants. Using a CIE1976 color-difference constraint, the initial CMYKlclm candidates were extracted, which kept the color-difference between the input CMY colors and colors for CMYKlclm candidates within an acceptable tolerance. Then, in order to reduce the use of unnecessary colorants based on the photo-ink separation passes, any candidates that exceeded the limitation of the total amount of colorant were removed. In addition, a dot-visibility metric was imposed on the quantity of light cyan and light magenta in dark regions. This was done to determine a CMYKlclm value that corresponded to an input CMY value. Finally, a lookup table composed of the CMY versus CMYlclm digital values was generated. Experiments confirmed that the proposed method could effectively reduce excessive amounts of colorant, while at the same time preserving good image quality.

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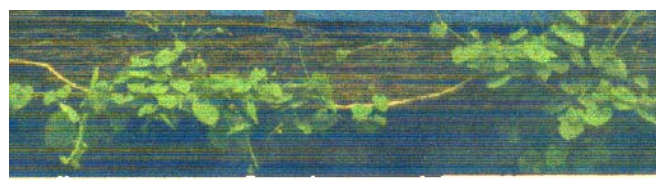
(a)



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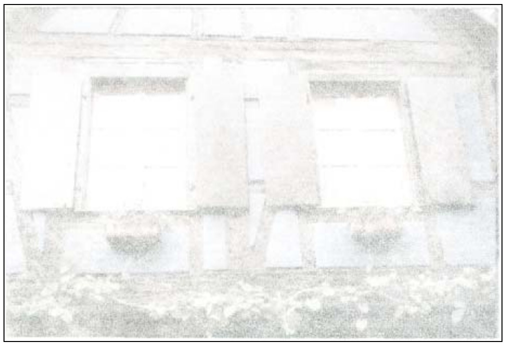

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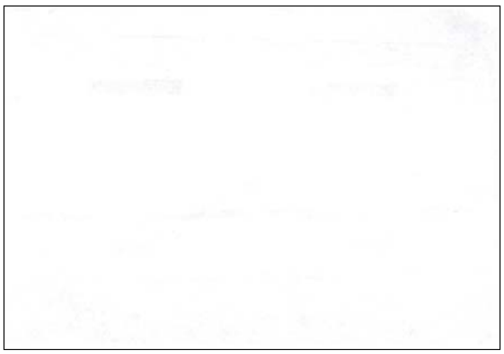

(f)

Figure 7. *The results of six-color separation for a 'house' image; (a) and (c) the resulting images, (b) and (d) cropped images, and (e) and (f) the reverse side of the resulting images for Agar's method and the proposed method, respectively.*

(a)

(b)

(c)

(d)

(e)

(f)

Figure 8. *The results of six-color separation for a 'room' image; (a) and (c) the resulting images, (b) and (d) cropped images, and (e) and (f) the reverse side of the resulting images for Agar's method and the proposed method, respectively.*