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Radiative transfer analysis of the effect of ink dot area on color phase in inkjet printing

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ABSTRACT

This study discusses a mechanism of inkjet printing and investigates the effect of ink contrast on the color phase of the printed object. Inkjet printing is a popular printing method for home use, but its color repeatability is occasionally broken. To verify this problem, we calculated the radiative transfer equation on the surface of an object printed by an inkjet printer, and the color was quantitatively estimated. The ink dot area and spectral reflectance of the printed samples were measured. Furthermore, the spectral reflectance of the objects printed with different dot areas were theoretically calculated. By comparing the measured and calculated reflectance, we estimated the scattering coefficient of the paper and absorption coefficient of the ink. We quantitatively calculated the color with the HSV color system. The hue changed with dot area rate. It is considered that this is caused by the broad range of the spectral absorption coefficients of inks. We believe that this study will aid the development of ink without color change and improve the color repeatability of inkjet printers.

1. Introduction

Inkjet printing is a printing method suitable for home use, in which small colored dots called “ink dots” are painted on the paper and the color contrast is controlled by increasing or decreasing the painted area of the ink dot called “dot area.” However, it has been reported that, in inkjet printing, the color phase of the painted objective changes when the contrast of the color is controlled by the density of the dot area [1,2]. In some cases, the phenomena of such various color appearances phenomena have been reported under the names “Bezold–Brücke hue shift,” “Abney effect” [3], and so on [4]. A thorough understanding of the mechanism of color change would help in improving the repeatability (constancy) of color.

According to a review by Foster [5], many researchers have studied the repeatability of color through theoretical and experimental approaches [5]. The review highlighted many advances, which were mainly achieved through qualitative approaches. Kuriki et al. [6] performed a series of asymmetric color-matching experiments by using two criteria: surface-color match and apparent-color match. They showed that, even with brief adaptation to the illuminant, the contribution of the surrounding stimulus is sufficiently large to achieve a fair degree of color constancy, but complete adaptation to the illuminant helps in achieving almost perfect color constancy. Uchikawa et al. [7] showed whether color constancy exploits the potential cue provided by the luminance balance of differently colored surfaces. Their results indicated that the luminance balance of surfaces with no chromaticity shift had clear effects on the observer's achromatic setting, which is consistent with our hypothesis made after the estimation of the scene illuminant based on optimal colors. Inks for inkjet printers have also been developed for ensuring adequate color quality and repeatability [8]. Montorsi et al. [9] studied correlations between the process parameters and the quality of decorated tiles on the basis of color and the presence of surface defects. They proposed an efficient method to control the final quality of the decorated tiles satisfying the quality standards required by market demand. Thus, the color has been studied in a broad context, but the color repeatability of objects printed by inkjet printers and the effect of the printing technique of the inkjet printer on the color phase have not been significantly investigated. Furthermore, light propagation on objects printed with dot ink has not been modeled.

In this study, the effect of dot area on the color phase is estimated and the mechanism of inkjet printing is discussed. The radiative transfer equation (RTE) is calculated on the surface of an object printed by an inkjet printer, and the color is quantitatively estimated. First, samples printed by monochromatic ink are prepared, and the spectral reflectance in the visible region (VIS) is measured. RTE is calculated, and the scattering coefficient of the paper and the absorption coefficient of the ink are estimated by comparison between the experimental and analytical results. The spectral reflectance of an object painted with an arbitrary dot area is calculated. The color is calculated from the measured and calculated reflectance with CIE,

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RGB, and HSV color systems. The effect of dot area on the color phase is discussed.

2. Experimental

2.1. Sample preparation

Monochromatic printed samples were prepared using cyan, magenta, and yellow inks. Graphics data are prepared using the vector graphics editor "Adobe Illustrator," and the dot area of the printed object was controlled. The CMYK color system in Adobe Illustrator was used. In Adobe Illustrator, color contrast is controlled by the computational value of the color spectral bar (*CSB*). *CSB* is set from 5% to 100% with 5% increments for each monochromatic color. Figure 1 shows graphics data in Adobe Illustrator for samples printed using cyan, magenta, and yellow ink. These data were printed on white gloss papers (SANWA SUPPLY, JP-EK5A4) using four color inkjet printers (Canon, iP2700) with only a cyan, magenta, or yellow ink container (Canon, BC-311) for each paper. The thickness of the white paper is 0.225 mm, and it is not transmissive. The inks are made of dye.

2.2. Dot area measurement

Printed samples were observed using a microscope (KEYENCE, VHX-5000) to estimate the rate of dot area ϕ. Figure 2 shows microscope images of a sample printed using cyan ink. The dot number and area of one dot were measured from the microscope images, and the dot area rate was calculated from the following equation:

$$\phi = \frac{nA_d}{A_0}, \tag{1}$$

where n is the dot number, A_d is the area of one dot, and A_0 is the area of the microscopic image.

Figure 3 shows the dot area rate as a function of *CSB*. As Fig. 2 indicates, the dot number and area of one dot could not be measured when *CSB* was greater than 65%, because there were too many overlapping dots to discriminate one dot and count the dot number. In this case, the rate of dot area ϕ is estimated from the approximated curve, as shown in Fig. 3. As this curve is different for each ink, the dot area must be measured for each ink.

2.3. Reflectance measurement

The spectral reflectances of the printed samples in the wavelength range of 400 nm to 740 nm were measured using a spectral colorimeter (CONICA MINOLTA, CM-2600d). This device has a single beam system. The light source is a Xenon lamp, and light irradiated on a sample and that reflected from a sample are diffusely reflected by the integrating sphere. These lights are dispersed by a plane diffraction grating and detected by a photodiode. The measurements were calibrated using a standard white plate (CONICA MINOLTA, CM-A145).

3. Numerical calculation

To determine the spectral reflectance of the painted object with arbitrary dot area, numerical calculation was conducted. Paper and dye ink can be considered scattering and absorptive continuous media, respectively. Therefore, the light propagation in the object printed by an inkjet printer is expressed in the following RTE:

$$\frac{1}{\beta_\lambda}\frac{dI_\lambda(\mathbf{r},\mathbf{s})}{dS} = -I_\lambda(\mathbf{r},\mathbf{s}) + \frac{\omega_\lambda}{4\pi}\int_{4\pi} I_\lambda(\mathbf{r},\mathbf{s}')\Phi_\lambda(\mathbf{s}'\rightarrow\mathbf{s})d\Omega, \tag{2}$$

where I [W m^{-2} sr^{-1}] is the radiative intensity, $\mathbf{r}$ is a positional vector, $\mathbf{s}$ is a directional vector, S [m] is a path, Φ [-] is a scattering phase function, and Ω [sr] is a solid angle. β [m^{-1}] is known as the extinction coefficient, and $\beta=\alpha+\sigma$, where α [m^{-1}] is absorption coefficient and σ [m^{-1}] is scattering coefficient. ω [-] is the single scattering albedo and is defined as $\omega=\sigma/\beta$, which gives the relative importance of scattering.

Figure 4 shows the numerical model. The analytical domain was a cuboid, the side surface of which was set as a periodic boundary. Therefore, the painted paper was modeled as an infinite parallel plane model. The thickness of a paper cell was 0.1 mm.

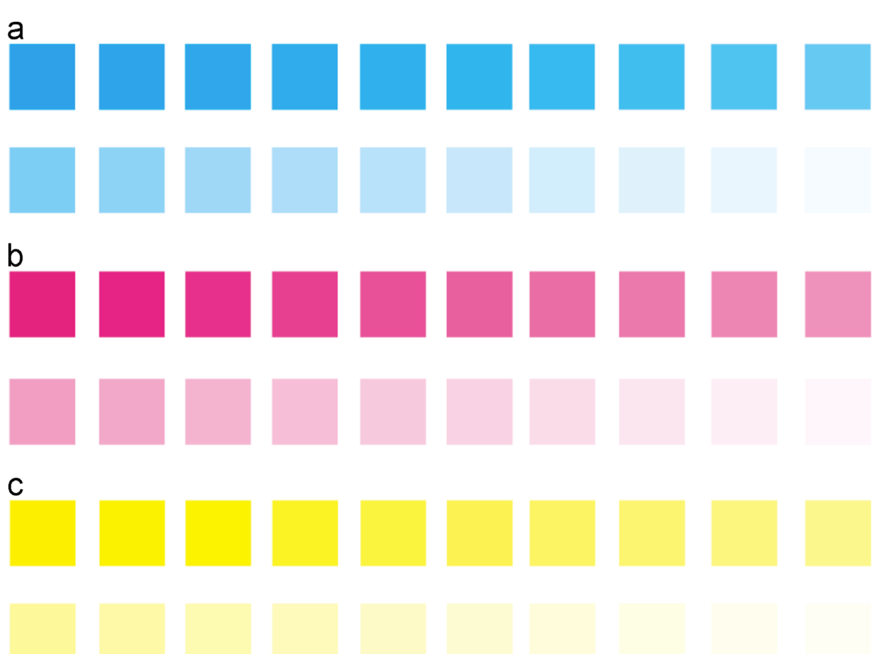

Fig. 1. Graphic data in Adobe Illustrator for samples printed with (a) cyan, (b) magenta, and (c) yellow ink.