A New Method to Quantitatively Evaluate Gradation Smoothness of Output Media

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Abstract

We have developed a new method of quantitatively evaluating the gradation smoothness of output media. In this method, virtual smooth curves are first estimated from real gradation curves, which are outputted by a real device with a digital gradation chart. Roughness components are then extracted by subtracting the estimated smooth curves from the actual gradation curves in a uniform color space. Lastly, roughness corresponding to human perception is evaluated with an estimating function based on the roughness components. We conducted visual experiments to optimize the estimating function using simulated prints with a silver-halide photographic printer. We obtained a correlation coefficient of more than 0.80 between the subjective values and the index by the estimating function. We confirmed its performance with print samples outputted by six electro-photographic printers currently on the market. We further implemented this evaluation method as an Adobe Photoshop plug-in module for easy use.

Introduction

The smooth gradation of output devices, especially color printers and displays, is exceptionally important to faithful image reproduction. Scenes of nature and subjects of fine color gradation, such as the sky and human skin, demand the reproduction of very smooth gradation. However, less-than-ideal performance of the output device and of such image processing as half-toning and color transformation can easily degrade smooth gradation.

There have been some reports about the smoothness evaluation not for output devices in total but for the processing of image data. Olson[1] analyzed artifacts in smooth color ramps generated by image processing such as color transformation using an ICC profile. He proposed some requirements for the profiles for smoothness. Ohno et al.[2] discussed methods of evaluating the tone reproduction of output modulated by image compression. Although they assumed that the output device is smoothly behaved, there are many cases in which a device does not satisfy their assumption because of defects in image processing such as half-toning. For such devices, it is difficult to create an ICC profile or a color LUT to realize smoothness in total. Fujino[3] evaluated image quality of several inkjet printers. He obtained discriminable lightness levels as an index of smoothness, but this has little correspondence with human perception.

The purpose of the method we have developed is to quantitatively evaluate the gradation smoothness of output devices which are under development or already on the market. We intend to obtain quantitative information about the quality of the device in terms of gradation smoothness based on a visual model. We expect to have a tool to assess the ability of output devices to reproduce smooth gradation.

In the past, such smoothness has been evaluated through visual assessment by an expert. Figure 1 is an example of a chart used for smoothness evaluation. We propose a novel method to replace such experimental assessment by an expert with a fully automated evaluation tool.

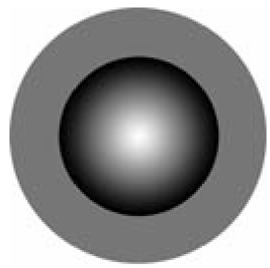


Figure 1. Chart for visual assessment of gradation smoothness.

In the following sections, we first explain the model proposed for use in our method of evaluation. Second, we describe a visual experiment to optimize the parameters of the evaluation method using a high-quality printer. Third, we describe the verification of the evaluation method using printers currently on the market. Finally, we introduce a tool that employs the method in the form of an Adobe Photoshop filter plug-in.

Proposed Method

Previously, we developed a noise evaluation method for input and output devices based on a model of human vision.[4,5] We use the same model to obtain the human perceptual smoothness of gradation patterns in the lightness, hue, and chroma coordinates in a uniform color space. We extract roughness components of the gradation along each coordinate.

A print of a digital gradation chart is first outputted by the printer to be evaluated. Second, the outputted print is digitized by a high-precision scanner. The digital image data of the outputted gradation chart are processed as follows.

Conversion Using Human Visual Model

The digitized gradation data are converted to CIE $L^*u^*v^*$ color space using a human visual model.[4,5] This model, illustrated in Figure 2, consists of the following four steps.

Step 1: The digitized data are adjusted to be colorimetric by compensating for such characteristics of the input device as gamma and color rendering. For example, when the color space of the input device is equivalent to sRGB[6] and also the image state is scene-referred, the formulas described in IEC 61966-2-1 are applied for compensation.

Step 2: The tristimulus values are converted into responses in the opposite color space, which consist of following three coordinates: red-green (C_{r-g}), yellow-blue (C_{y-b}), and white-black (Y), through the following equation.

$$\begin{bmatrix} C_{r-g} \\ C_{y-b} \\ Y \end{bmatrix} = \mathbf{M}_{oppo} \bullet \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 1.0 & -1.0 & 0.0 \\ 0.0 & 0.4 & -0.4 \\ 0.0 & 1.0 & 0.0 \end{bmatrix} \bullet \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \quad (1)$$

Step 3: Each response in the opposite color space is spatially filtered by means of corresponding human visual MTF responses. Each response is first transformed into the frequency domain via Fourier transformation and then is filtered by the corresponding spatial response of the human eye[7,8] in the Fourier domain. An example of the spatial characteristics of the human eye is given in Figure 3. We use the same response curve for C_{r-g} and C_{y-b} for model simplification. The filtered response is returned to the spatial domain using inverse Fourier transformation.

Step 4: The filtered responses are now transferred into CIE $L^*u^*v^*$ color space.

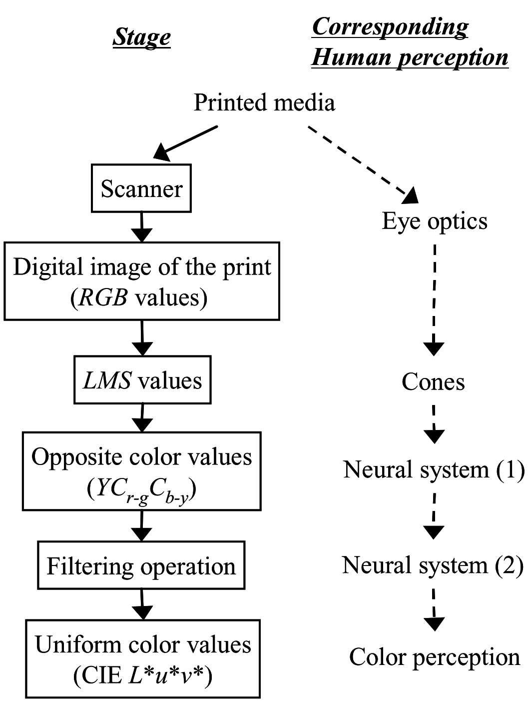


Figure 2. Human visual model used in this method.

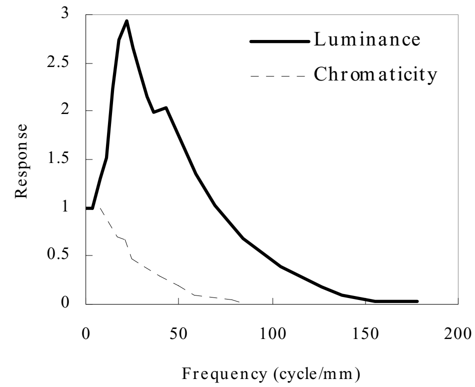


Figure 3. Spatial characteristics of the human eye in response to luminance and chromaticity.

Extraction of Roughness Components from L*u*v* *Gradation Data*

In the proposed method, roughness components against virtual smooth curves are extracted. If the gradation curve smoothly changes between the endpoints, it can be interpreted that the smoothness of the gradation is good. However, on many output devices, the gradation will not be smooth.

Extraction of the roughness components is one of the key points in the method. One idea for the solution may be to suppose some typical gradation curves in uniform color space which we can regard as ideally smooth. For example, suppose that a simple L^*-proportional curve is the ideally smooth curve, and the difference between the actual gradation data and the curve is obtained. But this will not work well in general, because a given printer may not be designed to produce such a gradation curve due to color reproduction between input and output.

We therefore introduce an estimated virtual smooth curve for each coordinate of $L^*u^*v^*$ from the actual $L^*u^*v^*$ gradation curve. In order to obtain the estimated curve, we average 20 smooth curves generated by Spline interpolation using two endpoints and two points which are randomly chosen along the actual curve. Each roughness component along the L^*, u^* and v^* coordinates is obtained by the difference between the virtual smooth curve and the corresponding actual curve, as seen in Figure 4.

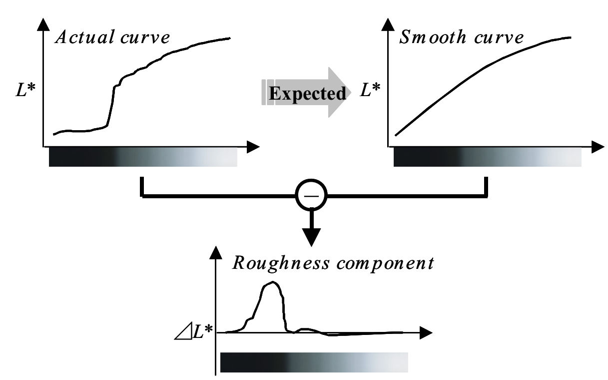


Figure 4. Extraction of roughness components.

Estimating Function Using the Roughness Components

In order to achieve a quantitative assessment which correlates highly with perception by the human eye, the estimating function which consists of the roughness components is supposed as follows:

$$Q_{rough}(x) = \alpha \cdot \left|D_{L^*rough}(x)\right| + \beta \cdot \left|D_{u^*rough}(x)\right| + \gamma \cdot \left|D_{v^*rough}(x)\right| \qquad (2)$$

where,

x : position along the gradation
$Q_{rough}(x)$: measurement of gradation roughness at x
$D_{L^*rough}(x)$, $D_{u^*rough}(x)$, $D_{v^*rough}(x)$: differential of L^*, u^* and v^* roughness component at x, respectively.
α, β, γ: weighting coefficients for each differential.

Each weighting coefficient of the estimating function is optimized by the visual experiment below.

Experiment to Optimize Estimating Function

Visual Experiment

Gradation Sample

Figure 5 shows three kinds of charts used in the visual experiment. The chart in Figure 5 (a) is used for the reference gradation which consists of two gradation images. The middle areas of the upper and lower gradation patterns of the reference have roughnesses corresponding to maximum and minimum roughness, respectively. Roughness is scored on a scale of 8 (maximum) to 0 (minimum). The center of the reference (appearing as white rectangle in the figure) is cut out to provide a window through which to compare the gradation samples with the reference place directly over them. Figure 5 (b) and Figure 5 (c) show examples of gray and color gradation samples, respectively.

In each sample, lines marked on upper and lower sides of each gradation pattern indicate positions to be visually evaluated in the experiment. We prepared six kinds of gradation images as the bases of the samples. Five bases are in color and one is gray. The distributions of the color bases were statistically extracted from 1535 DSC images including five scenes: evening, green, blue sky, sea, and human skin. The gradation samples were generated from the bases and roughness gradations. The roughness gradations were obtained from 12 existing printers. For simplicity, only the lightness component was modulated.

The experiments using gray samples and those using color samples were conducted separately. For each experiment, we prepared three sets of gradation samples. The first set was for familiarization of the observers with the experiment, so as to accustom them to the illuminant and to their surroundings. The second set was for adjusting the estimating function, and the third set was for testing of the estimating function.

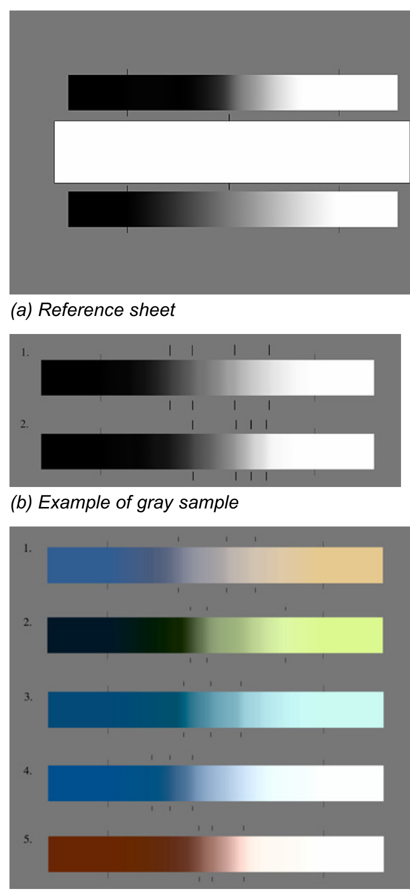
The gray set consists of 3 copies each of 6 gradation patterns for total of 18 gray samples. The color set consists of 3 copies each of 10 gradation patterns for total of 30 color samples. The samples were presented to the observers in random order. Because each gradation pattern appeared three times, their random appearance allowed the variance of the human evaluation to be assessed.

Because each copy of the six gray gradation patterns is marked with four evaluation points, and each copy of the 10 color gradation patterns is marked with three evaluation points, the estimating function was consequently adjusted and tested through the evaluation of 24 and 30 evaluation points, respectively.

All samples were printed by a digital color printer, the Pictrography 3000 by Fuji Photo Film Co., Ltd.

Experimental Procedure

We used a viewing booth, a Macbeth SpetraLight II and its "DAYLIGHT" illumination, which approximates to D70. Observers were requested to adjust the viewing distance between the samples and their eyes to about 30 cm. After familiarization with the procedure, each sample evaluation point for adjusting the estimating function and testing was compared with the reference, and the observers were requested to score the samples on a scale of 0 (minimum roughness) to 8 (maximum roughness) on a score sheet. If necessary, the observers were allowed to give a score higher than the reference maximum (i.e. 8).



(a) Reference sheet

(b) Example of gray sample

(c) Example of color sample

Figure 5. Charts for visual experiment.

Result

Gray Gradation Samples

Ten observers participated in the experiment. The averaged scores of visual evaluation (VE) of all observers were calculated as subjective evaluation values. We also obtained the quantitative measurement of each gradation sample using the proposed method.

The print samples were digitized using a flat-bed scanner, the Umax PowerLook 3000 by UMAX Technologies, Inc. with a resolution of 1200 dpi. We used only $|D_{L^*rough}(x)|$ for the differential component, since, by experimental design, the gray samples did not have gradation roughness except for lightness.

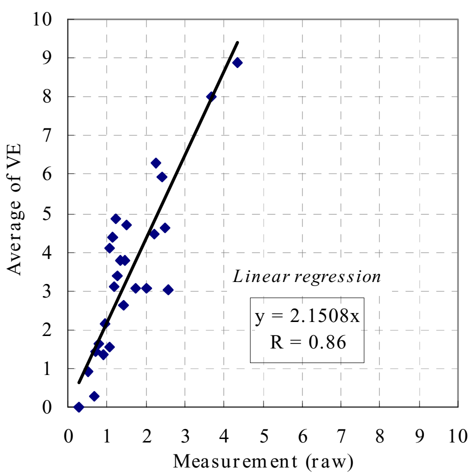
Figure 6 (a) show the distribution of the measurement and the experimental values for a set during which the estimating function was adjusted. The correlation coefficient is 0.86. Figure 6 (b) shows the results of a testing set applying the extracted estimating function. We used an index to quantify error using root mean square between the results and the ideal, which means that visual scores were equal to those of the measurement. In Figure 5 (b), the index is 1.05.

For verification, we checked the correlation between the subjective score and the measurement value by the estimating function described in equation (2).

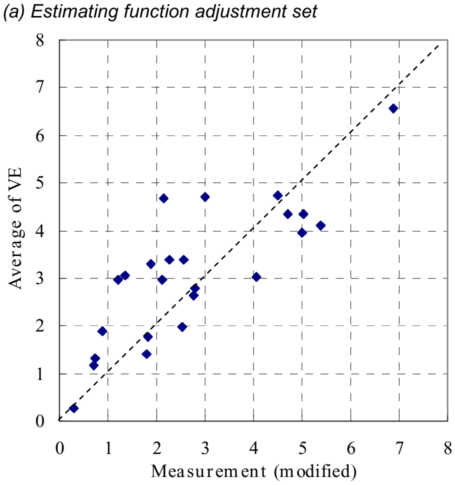
Color Gradation Samples

Similarly, we digitized each color sample using the same scanner, and calculated the differential components $|D_{u^*rough}(x)|$ and $|D_{v^*rough}(x)|$ in addition to $|D_{L^*rough}(x)|$. We obtained the averaged scores of 9 observers for the color gradation experiment. The estimating function was optimized by Solver, an application supplied with Microsoft Excel, in order to maximize the correlation coefficient between the measurement and the subjective values during adjustment of the estimating function.

Figure 7(a) shows the optimized results of its estimating function adjustment set. The correlation coefficient becomes 0.80 while the weighting coefficients α, β and γ are 0.6498, 0.1568, and 0.1934, respectively. The results of the testing set applied to the optimized estimating function are described in Figure 7 (b). The testing data are distributed along the dashed line, and the error index presented above is 1.12, which implies a similar accuracy both in gray and in color.

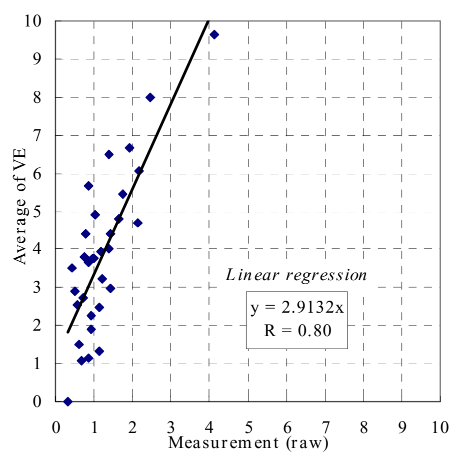


(a) Estimating function adjustment set

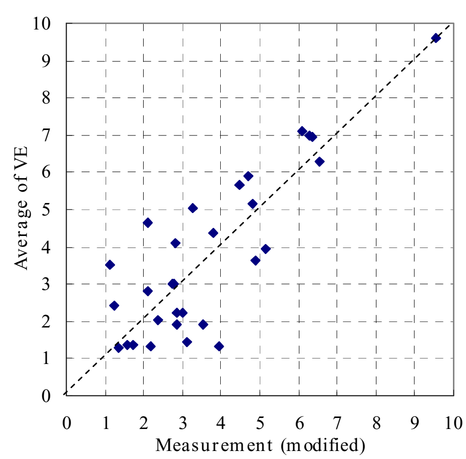


(b) Testing set

Figure 6. Results for gray samples.



(a) Estimating function adjustment set



(b) Testing set

Figure 7. Results for color samples.

Experiment Using Printers in the Market

We applied the developed method to printers currently on the market. Note that these printers use the electro-photographic process rather than the silver halide process used in Section 3.

Visual Experiment

Test Samples

We used six printers, shown in Table 1. The five color and one gray gradation patterns were printed by each printer at a resolution of 600 dpi. We then manually marked points to be evaluated for each gradation pattern. Figure 8 shows an example of samples outputted by one of the printers used.

Experiment Procedure

Experimental conditions and procedures were the same described in Section 3. The same reference gradation pattern used in the previous experiment (Figure 5 (a)) was used. In order to consider the variance of evaluation by observer, the experiment was intermittently performed in three trials with the observer.

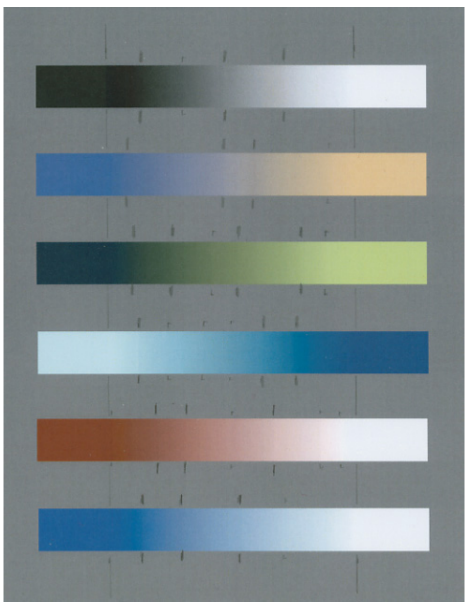


Figure 8. Gradation sample produced by electro-photographic printer.

Table 1: Printers used.

Category	Manufacturer	Model
Printer and copier	Canon	imageRUNNER
Printer and copier	Hewlett-Packard	Color LaserJet 5500dn
Printer and copier	Konica Minolta	bizhub C350
Printer and copier	Konica Minolta	bizhub C450
Printer and copier	Fuji Xerox	DocuCentre Color f360
Printer	Ricoh	imagio Neo C325it

Experimental Results

Figure 9 presents data from the observer that illustrates the relationship between the averaged score and a 95% confidence interval of the visual evaluation results. The four darkest dots indicate those results whose visual score was identical in all three trials (e.g. 3, 3, 3), while the 11 lighter points indicate results in which two scores were identical and the remaining score varied only by a value of one (e.g. 3, 3, 4). These results indicate that the observer could visually evaluate test samples with good stability.

Figure 10 shows the distribution of the subjective score and the measurement which is calculated by the estimating function for color samples. The darker and lighter dots indicate the same degree of stability of visual evaluation as in Figure 9. In these results, the error index, which was introduced in Section 3.2.1, is 1.20. This is similar to the results of experiments in Sections 3.2.1 and 3.2.2. Thus it is believed that each evaluation was performed with similar accuracy in spite of the difference of the media.

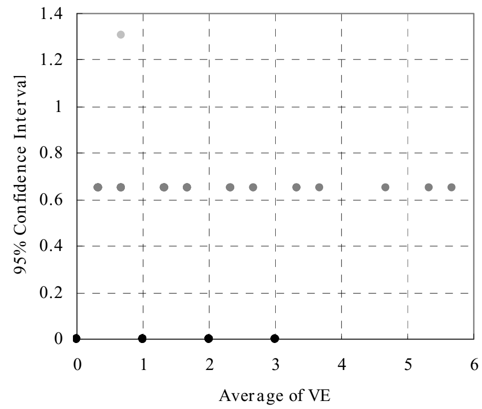


Figure 9. Stability of visual evaluation.

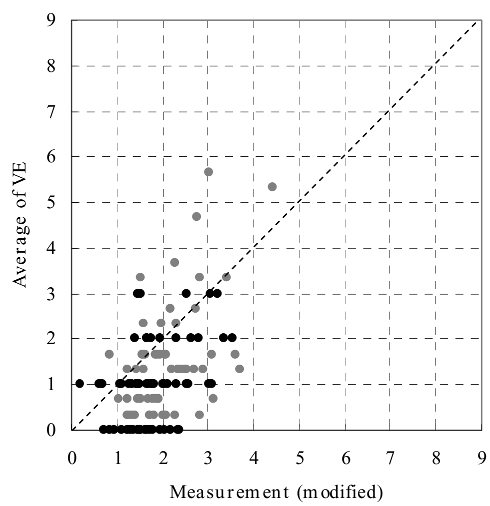


Figure 10. Results using on-the-market printers.

However there are several issues we should investigate in detail. In this experiment, we could not use samples which had roughness above a visual score of 6, since the samples are printed by standard, on-the-market printers without any modification. This is the reason for the limited distribution of roughness.

Another issue is that the distribution of data, especially in the area of low values, is slightly shifted to the right in the diagram. The paper used in electro-photographic printers has a physically rougher surface than the silver halide paper used with the Pictrography 3000, and we suspect that this difference caused the shift in the data.

We should investigate these issues and should improve the accuracy of the evaluation in the future.

Evaluation Tool

For the efficiency of image evaluation in practical settings, we have developed an image evaluation tool employing the proposed method. The tool was developed as a filter plug-in for Adobe Photoshop in order to remove problems of image file format. Figure 11 shows the graphical user interface (GUI) of the plug-in. In Photoshop, the plug-in is executed with the image selected by the rectangular tool. After setting parameters through the GUI, the evaluated smoothness is graphically displayed. This result can also be outputted in a text file, so that it is easily opened by spread sheet application software for further processing and analysis.

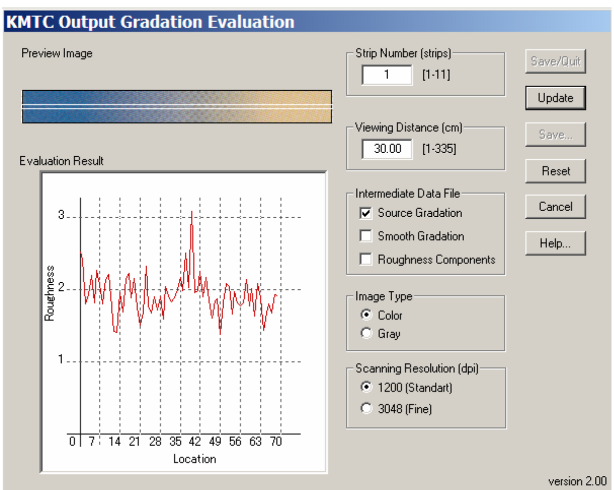


Figure 11. Graphical user interface of plug-in.

Conclusion

In this paper, we have proposed a new method of quantitative assessment of the smoothness of the gradation of output media. We conducted a visual experiment to obtain the optimized estimating functions for measuring gray and color gradation patterns. Using these functions, we confirmed that it is possible to evaluate gradation smoothness in approximation to human perception. With visual experiments using print samples from different types of color printers, we verified that the accuracy of the evaluations were similar.

Using the proposed method, we are able to evaluate a fundamental quality of output media in addition to other quantitative quality measures such as color, sharpness and noise. We will continue to examine and improve the accuracy of the measurement of various output media in the future.

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