Reproducing 3D Prints on Monitor by Relative-Glossiness Matching Technique

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Abstract

For over 3 decades, computer graphics technology has been developed to simulate physically accurate image of real scene. Meanwhile, useful tone mapping methods have been developed to map luminance range of the simulated image into that of usual monitor without perceptual distortion. However, it is difficult to reproduce accurate glossiness of real objects within the limited monitor luminance range. This also causes inaccurate glossiness sequence among several reproduced images. In this paper, relative-glossiness matching technique is proposed for reliable business to business (B to B) e-commerce system on 3D prints such as beverage cans, PET bottles, snack packages, and so on. The relative-glossiness-matching technique is introduced to preserve perceptual ratio of glossiness of the real 3D print objects in reproduced images. We also propose two operations to control surface-texture gloss and contrast gloss of reproduced images in Hunter's classification for physical gloss; adding Gaussian noise to surface normal in rendering process and scaling specular reflection in tone mapping. Procedure of subjective evaluation to determine the standard deviation of Gaussian noise and scaling factor for specular reflection is described. An experiment for the relative-glossiness matched images is performed using four types of real papers shaped into 3D cylinders. It was visually confirmed that the reproduced images preserved the glossiness sequence of the real 3D cylinder.

Introduction

There are many kinds of 3D prints such as beverage cans, PET bottles, snack packages, and so on in our life. In the field of B to B e-commerce system on designing and marketing of products, it is required to display measured or simulated images of the 3D prints. However, these images tend to be higher dynamic range than the luminance range of usual monitor because the 3D prints are made of smooth materials such as papers, plastics, and metals that have sharp and strong specular reflection. Therefore, the images of 3D prints cannot be displayed without certain image processing for dynamic range compression.

The dynamic range compression without perceptual distortion is referred to as tone mapping problem. In the early methods of the tone mapping, each pixel in an image was processed with the same mapping function, i.e., simple point processing operator.[1,12,16,17] These operators have been extended to empirical spatially varying operator to preserve local contrast.[13,18] On the other hand, the sophisticated methods based on the human visual system are recently proposed.[4,5,10,11] In their process, the adaptation luminance level on monitor is used to match the visual perception. However, the resultant values after mapping may still exceed the monitor luminance range since the luminance range is not considered in their process. This problem often occurs for reproducing the images of 3D prints of strong specular reflection. Therefore, additional compression which does not preserve the visual perception is required for displayable images of them. As a result, the glossiness of reproduced images $\tilde{G}_i$ becomes less than that of real objects G_i.

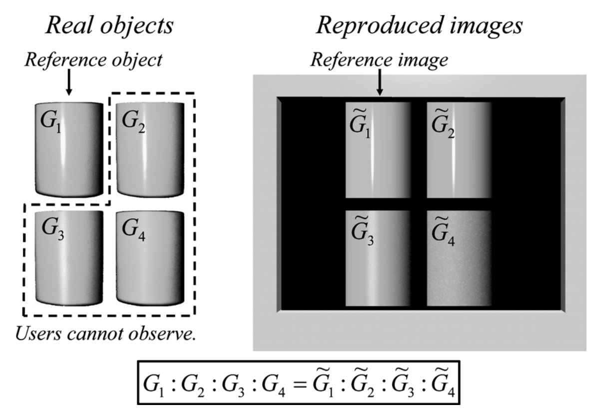


Figure 1. Relative-glossiness matched images.

In this paper, relative-glossiness matching technique is proposed for reproducing images of the 3D prints. As shown in Figure 1, this technique preserves the perceptual ratio of glossiness of real objects in reproduced images while it does not always preserve 'absolute' glossiness. The preservation of perceptual ratio leads to that of the glossiness sequence among reproduced images. Moreover, it gives us opportunity to predict glossiness of real objects using one reference object and reproduced images. The detail is described in the next section.

As long as the authors know, the relative-glossiness matching technique is not proposed yet. In this paper, therefore, feasibility study for the relative-glossiness matching technique is performed. In the next section, detailed concept and benefit of the relative-glossiness matching technique are described. After that section, the proposed two operations to control the glossiness of reproduced images is described. Procedure of subjective evaluation to determine the glossiness parameters in the proposed operations is also described. Finally, an experiment using four types of papers shaped into 3D cylinder is described.

B to B E-Commerce Using Relative-Glossiness Matched Images

As shown in Figure 1, the relative-glossiness matched images are reproduced to satisfy $G_1 : G_2 = \tilde{G}_1 : \tilde{G}_2$ where G_i and $\tilde{G}_i$ are glossiness of real objects and reproduced images respectively. This equation can be transformed to $R = G_1 / \tilde{G}_1 = G_2 / \tilde{G}_2$ where R means how many times the real objects are glossier than the images. If we have one set of real object and reproduced image, we can visually obtain the ratio R. Using the ratio R and another reproduced image with glossiness $\tilde{G}_i$, we can predict glossiness of corresponding real object with visual calculation of $G_i = R \times \tilde{G}_i$. The set to visually obtain the ratio R is called reference object and reference image in this paper.

Figure 2 shows an example of B to B e-commerce between a manufacturer and a designer using relative-glossiness matched images. Both of them have the same system and can observe the reference object and the reference image. Firstly, the designer visually obtains the ratio R by comparing the reference object and the reference image. Then, the designer designs an image of product predicting glossiness of the product based on the visual calculation $G_i = R \times \tilde{G}_i$. The designed image is sent to the manufacturer through the internet. After receiving the designed image, the manufacturer makes a prototype predicting the glossiness of product in the same way of the designer. The glossiness of prototype may be matched with the designer's imagination when the designer looks at the prototype delivered for confirmation.

In conventional B to B e-commerce system for this example, there is not the reference object and they predict the glossiness of product based on each experience. It is often necessary to manufacture revised prototypes several times until the designer is satisfied. The relative-glossiness matched images will reduce the manufacturing times since these images help them predict the glossiness of prototype in the same way. The procedure of glossiness predicting may not be easy or not robust for all e-commerce users. However, in the B to B e-commerce that is held by experts of much knowledge and experience in their fields, the predicting procedure will be easy and robust.

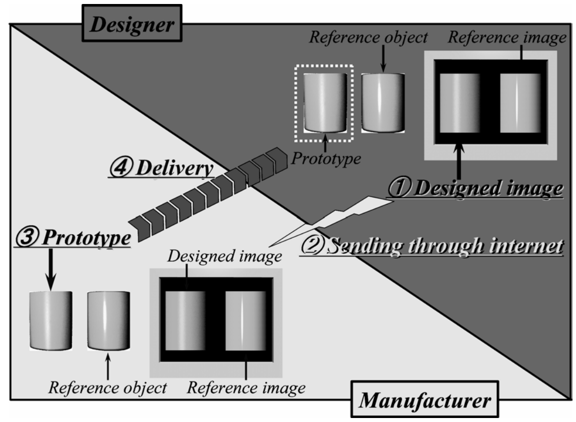


Figure 2. Example of B to B e-commerce system using relative-glossiness matched images.

Glossiness Control in a Reproduced Image

The proposed relative-glossiness matching technique does not require physically accurate rendered images since it allows difference between real objects and reproduced images in terms of glossiness. In other words, we have opportunity to control glossiness in rendering process besides tone mapping as long as other aspects such as color and shading are preserved.

Physical gloss that inspires us the perceptual glossiness is classified into specular gloss, sheen gloss, contrast gloss, bloom gloss, distinctness-of-image gloss, surface-texture gloss.[7,8] It has been studied to formulate perceptual glossiness with the physical glosses and there are several industrial standards using gonio-reflectance measurement.[8] However, the standards do not always correlate highly with our perceptual glossiness since most of them are only reflectance of a flat sample at one specular geometry such as 75/75 for papers. Furthermore, perceptual interaction among the physical glosses and glossiness of 3D shaped object are not considered in the standards. Therefore, we take two steps for reproducing the relative-glossiness matched images; propose of controlling technique of glossiness for reproduced images and subjective evaluation for determination of parameters used in the control.

Among the physical glosses, contrast gloss and surface-texture gloss are main factors for the papers used in our experiment described later. In this section, how to control these two physical glosses is explained. The surface-texture gloss for paper is usually grainy texture in highlight area as shown in Figure 3. The magnitude of surface-texture gloss is controlled in rendering process because it is due to micro-structure of the paper surface. The contrast gloss is contrast between luminance in highlight and non-highlight area. The magnitude of contrast gloss is controlled in tone mapping because monitor luminance range must be considered.

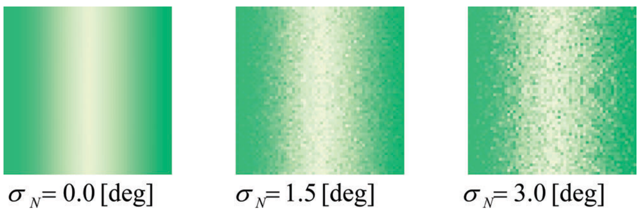


Figure 3. Glossiness variation with graininess

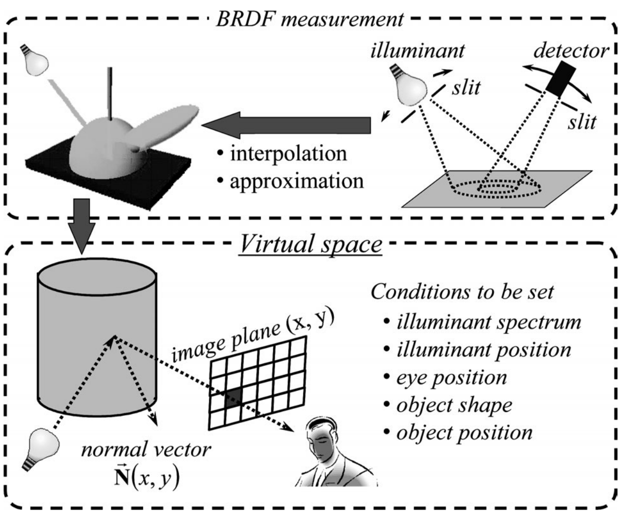


Figure 4. Scheme of rendering an image

Addition of Graininess in Rendering Process

Figure 4 shows scheme of rendering an image using physically-based computer graphics. After the homogeneous flat sample is prepared, its gonio-reflectances are measured at a lot of incident and outgoing angles. Note that the gonio-reflectances are spatially averaged in the aperture of the device used. Its bidirectional reflectance distribution function (BRDF) is obtained by approximating or interpolating the measured gonio-relfectances. Once the BRDF is obtained, an image can be rendered at any condition of illuminant position, eye position, and object shape and so on. The object shape is usually defined macroscopically such as cube, sphere, and cylinder because it is difficult to measure micro-surface structure and to reflect it in usual monitor of low resolution. The most obvious difference between the rendered images and real scene is that rendered images always have no texture in highlight area.

The purpose in this section is not to render accurate surface-texture gloss but to control its magnitude. To achieve the control, micro-surface structure is added to the macroscopic object shape. Each pixel denoted as (x, y) in image plane corresponds to one object point, i.e., one normal vector denoted as $\vec{\mathbf{N}}(x, y)$ in virtual space. New normal vector $\vec{\mathbf{N}}'(x, y)$ is calculated by adding stochastic noise to $\vec{\mathbf{N}}(x, y)$ at all the pixels (x, y). The stochastic noise is defined using angle θ between $\vec{\mathbf{N}}(x, y)$ and $\vec{\mathbf{N}}'(x, y)$. It is assumed that θ follows Gaussian probability distribution with 0 and σ_N for average and standard deviation respectively. The grainy texture in highlight area can be rendered by using new normal vector $\vec{\mathbf{N}}'(x, y)$ controlling its magnitude with σ_N. The variance σ_N ranges from 0 to a few degrees as shown in Figure 3. Diffuse reflection is hardly influenced within this range since it is nearly Lambertian characteristics for the paper. In other words, this addition of stochastic noise has little influence on reproduction accuracy of color and shading.

Scaling of Specular Reflection in Tone Mapping

Accurate reproduction of contrast gloss and that of color and shading are trade-off in tone mapping. For the accurate reproduction of contrast gloss, it is required to decrease luminances in non-highlight area. The resultant tone mapped images tend to be unsatisfactorily dark except highlight area. On the contrary, it is required to clip luminances in highlight area into the maximum monitor luminance for the accurate reproduction of color and shading. The resultant tone mapped images tend to have less contrast gloss than real objects have.

The purpose of this section is not to reproduce accurate contrast gloss but to control its magnitude. To achieve the control, it is proposed to map luminances of diffuse reflection and specular reflection in different ways. It is easy to separate diffuse and specular reflections in rendered images. The BRDF used in the rendering process is formulated as a sum of both reflections. Rendering using BRDF formula of diffuse (specular) reflection gives images of diffuse (specular) reflection.

Figure 5 shows scheme of the proposed tone mapping methods. It maps the rendered luminance range into monitor luminance range basically using color matching in CIELAB color space. The following procedure is point processing and coordinate (x, y) is omitted from the explanation. Firstly, tristimulus values of rendered image, (X_d, Y_d, Z_d) and (X_s, Y_s, Z_s), where subindices mean diffuse and specular, area transformed to (L_s^*, L_d^*, a^*, b^*). (a^*, b^*) are ordinarily transformed from (X_d, Y_d, Z_d) + (X_s, Y_s, Z_s). (L_s^*, L_d^*) are transformed as follows.

$$L^* = 116\left(\frac{Y_d + Y_s}{Y_n}\right)^{\frac{1}{3}} - 16$$
$$L_d^* = 116\left(\frac{Y_d}{Y_n}\right)^{\frac{1}{3}} - 16$$
$$L_s^* = L^* - L_d^* \quad (1)$$

where Y_n are tristimulus values of perfect reflecting diffuser obtained by rendering after putting the diffuser in place of an object in virtual space. The value L_d^* is brightness due to diffuse reflection and corresponds to shading. The value L_s^* is brightness increase due to specular reflection and causes contrast gloss. a^* and b^* correspond to color of illuminated object for non-highlight area and color of illuminant for highlight area. Secondly, L_s^* is scaled to control contrast gloss.

$$\tilde{L}_s^* = cL_s^* \quad (2)$$

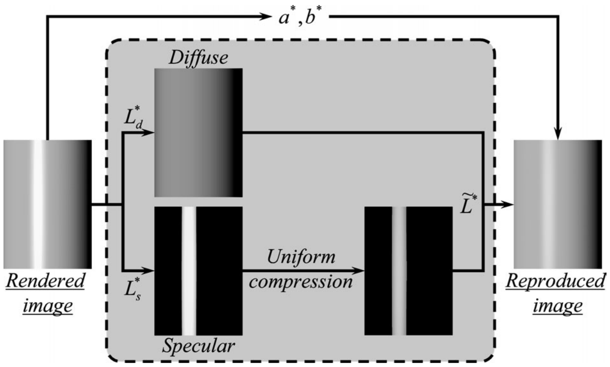


Figure 5. Scheme of the proposed tone mapping

where the scaling factor c is a parameter for the magnitude of contrast gloss in tone mapped images. Because the scaling of L_s^* is spatially uniform, size of highlight area is not hardly distorted perceptually by the proposed tone mapping. Thirdly, total brightness of both reflections is calculated as summation.

$$\tilde{L}^* = L_d^* + \tilde{L}_s^* \tag{3}$$

Finally, $\left(\tilde{L}^*, a^*, b^*\right)$ are transformed into tristimulus values $\left(X^{monitor}, Y^{monitor}, Z^{monitor}\right)$ based on the maximum tristimulus values of monitor $\left(X_n^{monitor}, Y_n^{monitor}, Z_n^{monitor}\right)$.

Because maximum displayable $\tilde{L}^*$ is equal to100, the maximum value of scaling factor c below which all the pixels are displayable is approximated as follows.

$$c_{\max} \cong \frac{100 - L_{d,\max}^*}{L_{s,\max}^*} \tag{4}$$

where $L_{d,\max}^*$ and $L_{s,\max}^*$ are L_d^* and L_s^* of the pixel that has the maximum brightness in a rendered image. Equation (4) is derived from equation (2), (3), and the approximation that L_d^* can be regarded as constant in highlight area.

Determination of the Relation Between Glossiness and Glossiness Parameters

To obtain the relative-glossiness matched images, σ_N and c must be determined for each image based on glossiness of real objects. Two different subjective evaluations are required for the proper determination of σ_N and c. One is evaluation to obtain 'absolute' glossiness G_i of real objects. The other is evaluation to obtain the relation $\tilde{G}_i(\sigma_N, c)$ between the glossiness parameters and 'absolute' glossiness for each image. After these evaluations, σ_N and c can be chosen to satisfy $G_i : G_j = \tilde{G}_i : \tilde{G}_j$. The evaluation for relation $\tilde{G}_i(\sigma_N, c)$ will be successively performed using a set of images with various parameters because 'absolute' glossiness range of displayable images is not so wide. However, the evaluation for glossiness G_i will be failed because real objects have quite wide range of 'absolute' glossiness due to quite wide range of luminance.

We roughly determine σ_N and c by one subjective evaluation in which observers are asked to evaluate not 'absolute' glossiness but perceptual ratio of glossiness. In this approach, it is evaluated how close the perceptual ratio between reproduced images $\tilde{R}\left(= \tilde{G}_i / \tilde{G}_j\right)$ is to that between real objects $R\left(= G_i / G_j\right)$. The reason why we use this approach is that the evaluation of perceptual ratio between real objects is robuster than that of 'absolute' glossiness for each real object. The detail of evaluation to obtain the relative-glossiness matched images is described below.

1. The glossiest real object (G_{ref}) is referred to as the reference object.
2. One reproduced image ($\tilde{G}_{ref}$) of the reference object is referred to as the reference image.
3. One object (G_i) is chosen from the others and a set of reproduced images ($\tilde{G}_i^j$) for it with various combinations of c_N and c are calculated.
4. The object chosen is put beside the reference object and the set of reproduced images is displayed beside the reference image one after another. The objects and the images are observed in haploscopic vision.
5. Subjects are asked to evaluate how close the perceptual ratio $\tilde{R}_i^j\left(= \tilde{G}_{ref} / \tilde{G}_i^j\right)$ between the reference image and the each reproduced image is to that $R_i\left(= G_{ref} / G_i\right)$ between the reference object and the object put beside. The reproduced image that is evaluated as the closest, i.e., minimizes $\left|R_i - \tilde{R}_i^j\right|$, is the relative-glossiness matched image.
6. Repeat operation 3 to 5 until all the objects are chosen.

Note that the relative-glossiness matched images obtained by this subjective evaluation depend on the choice of the reference image and there are other combinations of images that preserve the perceptual ratio of glossiness.

Experiment

In this section, an experiment for reproducing relative-glossiness matched images was performed using four different papers (cast-coated, art-coated, matte-coated, and uncoated in glossiness sequence) solid printed with the same green ink.

Preparation of Cylindrical Printed Papers

Shape of the paper to be reproduced using relative-glossiness matching technique was chosen as a cylinder. This is because scene luminance of complexly shaped objects is variable with slight variations of position and azimuth orientation of the objects. Four cardboard cylinders were wrapped in black papers. Then, they were wrapped in the printed papers. The black papers prevent transmitted light through the printed paper from outgoing by reflecting on the cardboard and transmitting again. The size of the samples was 8.5 cm in diameter and 10 cm in height. Observation geometry for the cylindrical samples was shown in Figure 6. A metal halide lamp (HAYASHI WATCH-WORKS Co., Ltd., LuminarAce LA-180Me-R) was used for the illuminant. The intensity of the illuminant was adjusted to reach 110 cd/m^2, i.e., photopic condition.

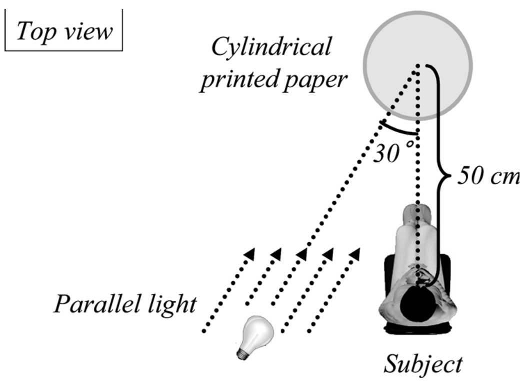


Figure 6. Observation geometry in our experiment

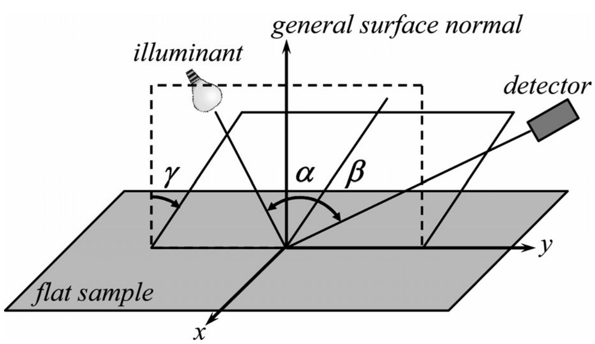


Figure 7. Measurement geometry of the gonio-spectro-photometric colorimeter GCMS-4

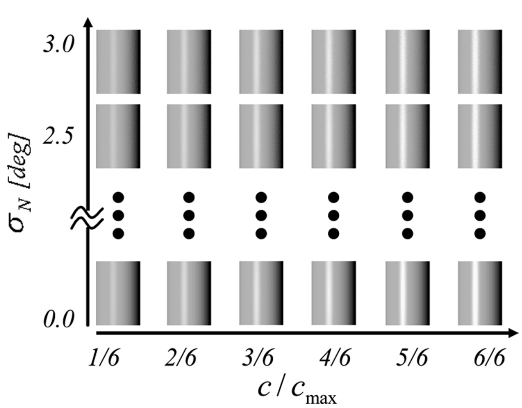
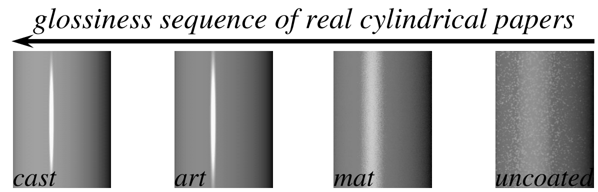
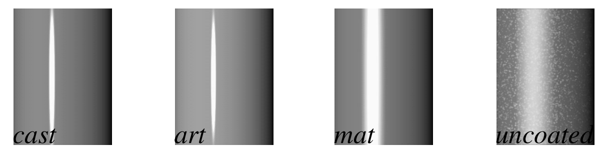


Figure 8. Reproduced images of Mat-coated paper



(a) Relative-glossiness matched images



(b) Colorimetrically reproduced images

Figure 9. Reproduced images for comparison

Reproducing Images with Various Glossiness

To simulate the observed scene luminance images, the spectral distribution was measured by putting an white reflectance standard and an spectro-radiometer in places of the cylindrical sample and eye of the geometry respectively. The BRDFs of four flat printed papers made of the same ink and papers with the cylindrical samples were also measured with the gonio-spectro-photometric colorimeter GCMS-4 (MURAKAMI COLOR RESEARCH LABORATORY). As shown in Figure 7, it has three controllable angles α, β, and γ. The measurement conditions are described below.

- Angles; Combinations of α = -70, -60, …, 70, β = 0, 10, … , 70, and γ = 0, 5, 10, 15, 30, 45, 60 in degree. In order to measure sharp characteristics of specular reflection, β = -α-5, -α-4, …, -α+5 for all the α were added when $\gamma \le$ 15.
- Wavelength; 390 nm to 730 nm at an interval of 10 nm.
- Aperture; the greater β is, the larger size of measured area is. The minimum size is 8 × 16 mm^2 at β = 0. The maximum size is 8 × 47 mm^2 at β = 70.

The measured BRDFs were approximated with Torrance-Sparrow model and Oren-Nayar model that are models for specular and diffuse reflection respectively.[9,15]

Based on the BRDFs, images for each cylindrical sample were rendered with seven kinds of σ_N that ranged from 0.0 [deg] to 3.0 [deg] at an interval of 0.5 [deg]. Each rendered image was tone mapped with six kinds of c that ranges from $c_{max} \times 1/6$ to $c_{max} \times 6/6$ at an interval of $c_{max} \times 1/6$. Namely, 42 images were reproduced for each cylindrical sample. Some of the rendered images are shown in Figure 8.

Subjective Evaluation

The cast-coated cylindrical sample, which was the glossiest in the samples, was chosen as the reference object. Within the reproduced images of it, the glossiest image, reproduced with σ_N = 0.0 [deg] and $c = c_{max} \times 6/6$, was chosen as the reference image. SONY Trinitron MultiscanTC (19 inch) was used for monitor. 15 subjects were involved in the subjective evaluation. After 10 minutes adaptation for haploscopic vision, they evaluated 'distance' of the perceptual ratios with five degrees of 'close', 'slightly close', 'fair', 'slightly far', and 'far'.

Results

The method of successive categories was used for analysis of the evaluation results. The images evaluated as the best included the reproduced images of σ_N = 0.0 and $c = c_{max} \times 5/6$, σ_N = 2.0 and $c = c_{max} \times 2/6$, and σ_N = 2.0 and $c = c_{max} \times 1/6$ for the art-coated, matte-coated, and uncoated cylindrical samples respectively. These best images are shown in Figure 9 (a).

The authors visually confirmed that the best images shown in Figure 9 (a) preserved the glossiness sequence of the cylindrical samples. These images also preserved the color and shading of the samples. To compare the best images to other conventional tone mapped images, we reproduced images for the cylindrical samples using colorimetric reproduction and human visual system based tone mapping.[10] The clipped images are shown in Figure 9 (b). The image for matted-coated cylindrical sample looks the glossiest in the images because of the clipping. On the other hand, the human visual system based tone mapped images resulted in unsatisfactory color reproduction except highlight area, although the parameter of the method, e.g., the ratio of global and local adaptations, was widely varied.

It is not confirmed that the best images preserve the perceptual ratio of the samples. This confirmation will be difficult since 'absolute' glossiness of the cylindrical samples may not be successively obtained because of their wide range of luminance. Furthermore, we have to find the sample which has no glossiness to quantify the perceptual ratio of glossiness since values obtained by subjective evaluation are only interval scales.

Conclusions

Because of low luminance range of monitor, glossiness of real objects tends to be inaccurately reproduced. This problem also causes inaccurate glossiness sequence among several reproduced images. The relative-glossiness matching technique was proposed for reliable B to B e-commerce system on the 3D prints. The relative-glossiness matched images preserve the perceptual ratio of glossiness of real objects in reproduced images. The standard deviation of Gaussian noise in rendering process and the scaling factor of specular reflection in tone mapping were proposed for glossiness parameters in reproduced images to control surface-texture gloss and contrast gloss. The glossiness parameters were determined by subjective evaluation in which subjects were asked to evaluate how close the perceptual ratio between reproduced images was to that between real objects. An experiment of the relative-glossiness matching was performed using four types of papers that were solid printed with the same green ink. It was visually confirmed that the resultant images preserved the glossiness sequence of the papers. This paper implies that how large the gamut of displayable images, not simple color patches, is and what the best solution is if accurately reproduced images exceed the gamut should be studied. The relative-glossiness matching technique is one of the solutions and is still at a phase of feasibility study. The better solutions must be found based on further studies of visual perception of two dimensional images.

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Biography

Ishii Toru was born in Chiba, Japan, on March 12, 1979. He received his B.E. and M.E. degrees in department of information and computer science from Chiba University in 2001 and 2003, respectively. Now he is a doctor course student in Chiba University. His research interests include human vision, image quality, color management, and computer graphics.