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INVITED PAPER

Simultaneous Reproduction of Reflectance and Transmittance of Ink Paintings

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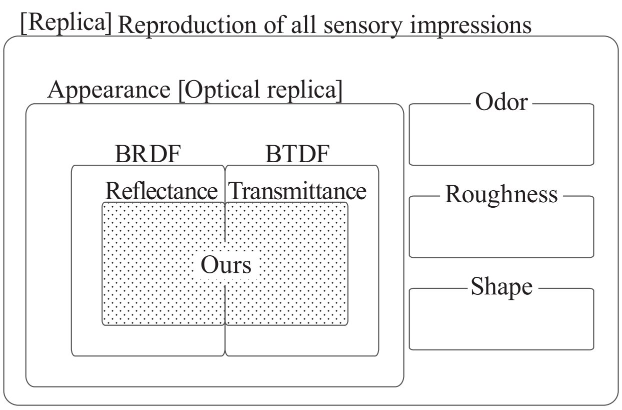
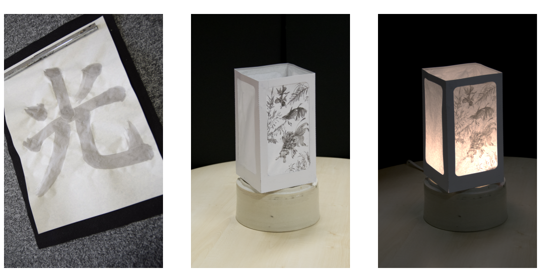


Fig. 1: Relationship between related replicas and ours.



(a) Appearance of ink painting (b) Lantern under external indoor light (c) Lantern lit from within

Fig. 2: Appearance of ink painting and lantern.

SUMMARY The purpose of our research is to reproduce the appearance of frangible historical ink paintings for preserving frangible historical documents and illustrations. We, then, propose a method to reproduce both reflectance and transmittance of ink paintings simultaneously by stacking multiple sheets of printed paper. First, we acquire the relationship between printed ink patterns and the optical properties. Then, stacking printed multiple papers with acquired ink pattern according to the measurement, we realize to fabricate a photo-realistic duplication.
key words: *reflectance, transmittance, fabrication*

1. Introduction

Japan has a long history and many important historic cultural assets. However, many are facing the danger of degradation from aging. In particular, works produced on paper such as ink paintings may lose their value as cultural assets when continuously illuminated with light, because the paper texture will be destroyed, and characters and pictures drawn in ink will lose their unique feel. Therefore, digital archiving, in which various aspects of such works are measured and stored as digital data, is becoming widely adopted to pass these cultural assets on to generations of the long-term future.

The virtual museum is another proposed effort, in which anyone can easily and remotely access data on cultural assets. However, in a virtual museum images and videos are simply shown on a screen. The virtual cultural assets cannot be experienced by the senses as they are in reality, and the intrinsic unique feel of the works cannot be experienced. Therefore, technology to create replicas that precisely reproduces the overall sensory impression, or "feel" of the object, is desirable. In particular, reproduction of the feel of ink paintings that are precious cultural assets found all over Japan is important.

The "feel" of ink paintings comes from diverse factors, and perfect reproduction should consider many elements such as appearance, odor, roughness, and shape. Cultural assets that are primarily appreciated visually, for instance ink paintings, strongly emphasize the reproduction of optical properties. Therefore, this paper discusses the impression of the objects from the viewpoint of optical properties, and does not consider other aspects such as odor, roughness, and shape. A replica that precisely reproduces optical properties of the target is defined in this article as an "optical replica", and the objective of this study is to create replicas that simultaneously reproduce the reflectance and transmittance of the original works as a first step towards the establishment of methods to produce the optical replica. Figure 1 shows how replicas reproduced in this study are positioned in comparison to related replicas produced from other aspects. Ink paintings are generally flat, but some have a partially rough surface from creases and folds. These regions are different from flat regions, but were not investigated in this study as the difference is considered to arise from differences in the surface shape and not from the original inking.

Ink paintings considered in this study were produced solely with ink and brush. Although the shades of ink and brushwork used by the painter affect both the surface reflectance and transmittance, ink paintings are typically appreciated when placed on a desk or a wall, and therefore reflected light is generally observed (Fig. 2 (a)). However, the transmittance of ink paintings has also been used from

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ancient times, such as in lanterns that impressively illuminated from inside (Fig. 2 (b), (c)), Japanese kites that fly with skylight as the backdrop, and Nebuta ceremonial floats. Therefore, the transmitted light can be appreciated in addition to reflected light, and consideration of both reflectance and transmittance is important when creating replicas. Much important information is known in regard to transmitted light in the field of historiography.

In this study, digital data of ink paintings was first generated after measuring both the reflectance and transmittance of the works simultaneously. Next, multilayered prints that reproduced both reflectance and transmittance of the measured paintings were created using a commercially available inkjet printer.

2. Related work

Many archiving methods based on measurement to accurately record various features of cultural assets have been proposed. The Kyoto Prefectural Library and Archives is currently recording and preserving old documents, such as the "Archives of Toji temple contained in one-hundred boxes (Toji Hyakugo Monjo)", listed in the Memory of the World Register United Nations Educational, Scientific and Cultural Organization (UNESCO) [1]. The Nara National Museum has a digital archive of the "Hoke-kyo," which is registered as an important cultural property [2]. These are examples that show efforts to record and preserve old documents as digital data, which are widely conducted. To record more precisely, Tominaga and others used multispectral imaging of paintings to create records of the spectroscopic properties intrinsic to the paintings without any dependence on the light environment [3]–[5]. Recording of shape and size in addition to colors is important in cultural assets such as great Buddha statues. Oishi et al. [6] obtained the three-dimensional shape of the actual Nara Great Buddha Statue using a range sensor. Archiving in recent years has not been limited to tangible objects, but is also adopted to intangible cultural assets, including traditional dance and Kabuki. Hachimura [7] used an optical motion capture system to record complex dance moves as digital data. There are also reports on efforts to realistically reproduce these cultural assets. Research to reproduce measured characteristics that determine the "feel" of works using computer graphics includes reproduction of reflection properties of lacquerware [8] and Noh costumes [9]. Rouiller et al. [10] worked on 3D-printed reproduction of optical properties of objects based on the spatially varying bidirectional reflectance distribution function (svBRDF), but they did not consider transmitted light. Dong et al. [11] studied reproduction of the bidirectional scattering surface reflectance distribution function (BSSRDF) of objects, but they focused on multiple subsurface scattering, which cannot be applied to objects with strong transmittance. Toppan Printing Co., Ltd. established a system to visualize digital data obtained from the important cultural property "Genre Scenes in Kyoto (Rakuchu-rakugai-zu)" using virtual reality [12]. Kakuta et al. [13] developed a system with high level of immersion by presenting intense images of Asuka-kyo using a head-mounted display (HMD). These efforts all present realistic visuals through various methods. However, optical properties such as reflection properties are not reproduced.

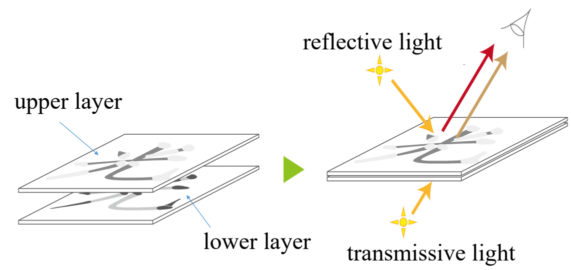


Fig. 3: Multilayer printing structure for reproducing reflective and transmissive light.

The present study therefore investigated many ink paintings that remain as important cultural assets, and aimed to create replicas that simultaneously reproduce the reflectance and transmittance of the works. Reflective light is typically appreciated in ink paintings as mentioned above, and therefore these are exhibited on a desk or wall in art galleries and museums.

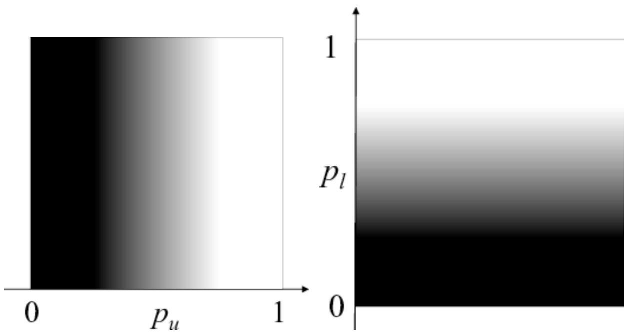
Transmitted light that can be seen through from the front of an object is affected by the foundation of the mounting of the work. Regarding the foundation that the ink painting is positioned on as an integral part of the ink painting, and reproducing the total reflection properties would make possible exhibition of reproductions that look the same as the originals. However, using this method, the ink painting and foundation cannot be separated. There will be severe limitations on how the works can be exhibited, and the appearance when appreciating the ink painting up close cannot be reproduced. In contrast, the proposed method, in which reflectance and transmittance are simultaneously reproduced, is superior because it can, in principle, reproduce the works regardless of the type of foundation, and even whether one exists.

3. Replicas that simultaneously reproduce reflectance and transmittance

3.1 Simultaneous reproduction of reflectance and transmittance using multilayer printing structure

The simplest method to reproduce pictures and characters produced on paper, such as in ink paintings, involves digitizing the target using an image scanner or digital camera and then printing the obtained image using a printer. However, a simple printing can only control the density of toner or ink that is applied to the surface and therefore primarily reproduces only the reflectance characteristics of the surface.

Ink paintings having the same reflectance characteris-



(a) upper layer color (b) lower layer color

Fig. 4: Gradations for creating look up table.

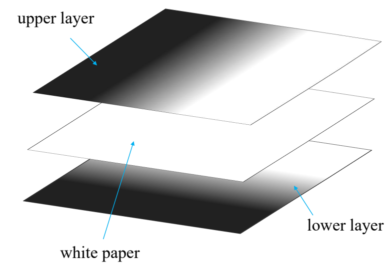


Fig. 5: Inserting one sheet of blank printing paper between two printed papers.

tics can have different transmittance, for example because of different degrees of penetration of ink into the paper, and therefore the transmittance is important in addition to the reflectance when reproducing the "feel" of a work. Therefore, reproduction by standard printout from a printer is difficult, and hence simultaneous control of reflectance and transmittance is necessary to reproduce such differences.

Therefore, in this research, prints of various patterns were created on different papers using an inkjet printer, and then these were combined in multiple layers to form a replica that reproduces both the reflectance and transmittance of the original ink painting, as shown in Fig. 3.

This setup is defined as a "multilayer printing structure" in this study. Multilayer printing structure replicas consisting of two layers, upper and lower, were prepared. Both reflectance and transmittance may be simultaneously reproduced by controlling the density of ink to be printed on both upper and lower layers of the multilayer printed structure. Increasing the opacity of printed papers should decrease the transmittance, and therefore tracing paper, with relatively high transmittance, was used as the printing paper to more easily reproduce high transmittance.

3.2 Generation of a lookup table

The ink density at a point of the upper and lower layers (upper and lower layer "grayscale values", respectively) is defined as p_u and p_l, respectively. One method to determine these ink densities is a model-oriented approach based on the Kubelka-Munk theory [14]. To apply this theory, however, it requires sufficiently precise measurements of physical parameters of printing paper and ink density, and it cannot be executed easily. Moreover, the solutions corresponding to the desired reflectance and transmittance are not always numerically stable.

Therefore, we used a sample-based approach that is not adversely affected by detailed physical parameters or unstable solutions. The possible values of p_u and p_l, are limited to 256 steps between 0.0 and 1.0. A multilayer printing structure containing all 256^2 combinations of p_u and p_l is created and saved as a lookup table. Reverse lookup of this lookup table can enable deduction of the p_u - p_l combination that reproduces the desired reflectance and transmittance at a given sampling point.

A multilayer printing structure is created by stacking together two sheets, each having unidirectional gradation, as shown in Fig. 4. The gradation contrast uniformly shifts in 256 steps and the gradation direction of the two sheets are is orthogonally arranged. Figure 4 (a) and (b) show illustrate gradation patterns used in the upper and lower layers, respectively. The square region, in which the gradation pattern is printed, covers all combinations of upper and lower layer grayscale values (p_u and p_l, respectively), and the relation between arbitrary p_u and p_l versus reflectance $r(p_u, p_l)$ and transmittance $t(p_u, p_l)$ can be each obtained in one imaging session.

3.3 Determination of upper and lower grayscale values from reverse lookup of the lookup table

Given the desired reflectance R and transmittance T, upper and lower layer grayscale values (p_u and p_l, respectively) that minimize this function are derived:

$$\underset{p_u, p_l}{\operatorname{argmin}}(|R - r(p_u, p_l)| + |T - t(p_u, p_l)|). \tag{1}$$

This process is conducted for all points at the target surface where reflectance and transmittance are to be reproduced, and the p_u and p_l values to be printed on the multilayer printing structure are obtained together with the printing pattern. A replica is then created by printing these patterns and stacking them together. This method does not assume a mathematical model for the printing paper and ink, which is beneficial because measurement of physical parameters is not necessary and changes in the paper and ink can be handled through simple measurements.

4. Improving the reproducible dynamic range

Reproduction of reflectance and transmittance in the proposed multilayer printing structure may in some cases be impossible because of printing paper and ink properties. The following two methods are proposed to address this problem:

4.1 Compression of dynamic range

If the variety of reproducible reflectance and transmittance of the multilayer printing structure is insufficient, or in other words, the dynamic range of the reproduction system is insufficient for the target, irreproducible regions appear on the replica. These regions are not only physically incorrect, but also have very adverse effects on the reproducibility of the "feel" of the work.

Therefore, the dynamic range of the target ink painting is compressed (scaled) to a range that can be reproduced with the multilayer printing structure. This minimizes adverse effects on reproduction of the feel, although the reflectance and transmittance contrast will be smaller as a whole. In practice, the upper and lower layer grayscale values (p_u and p_l, respectively), are obtained with the following equation, in which the desired reflectance R and transmittance T are scaled with coefficients α_r and α_t:

$$\underset{p_u, p_l}{\operatorname{argmin}} \left(|\alpha_r R - r(p_u, p_l)| + |\alpha_t T - t(p_u, p_l)| \right). \tag{2}$$

4.2 Insertion of a blank sheet

The above method is always applicable when appropriate coefficients α_r and α_t are selected, but physical reproducibility is not guaranteed. We therefore attempted to create a replica closer to the original by changing the multilayer printing structure.

Tracing paper with relatively high transmittance is used as printing paper in the multilayer printing structure, and thus the dynamic range may be too narrow depending on the properties of the target object. Insertion of blank printing paper between the printed two sheets to increase the thickness, as shown in Fig. 5, changed optical properties of the multilayer printing structure and thus the reproducible dynamic range.

Insertion of blank paper results in an obvious reduction in the transmittance of multilayer printing structures made of semitransparent printing paper. Changes in reflectance was also anticipated. In other words, illumination of light on an opaque object surface does not change the reflectance, because reflection only occurs at the surface; however, the tracing paper used in this study was semitransparent, with relatively large transmittance. Light penetrating into this semitransparent object changes direction with internal subsurface scattering. Increasing the thickness of the object therefore increases the relative amount of light that scatters within the object, and the amount of light that exits together with the reflected light also increases, because of backscattering. Therefore, the apparent reflectance was also expected to increase.

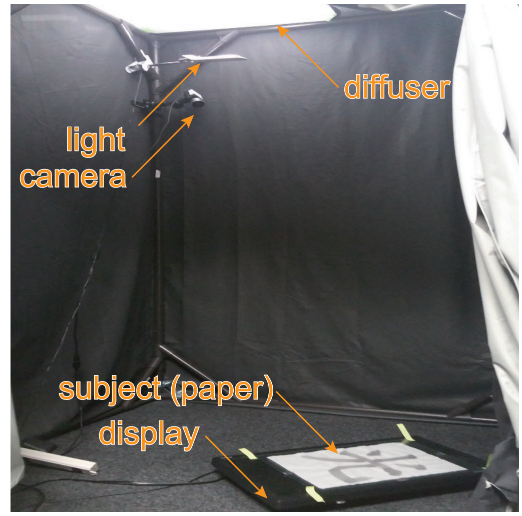


Fig. 6: Experimental environment.

(a) Reflected light (b) Transmissive light

Fig. 7: Images of reflecion and transmission of sample.

5. Creation of replicas and verification of performance

In this section, the actual creation and performance verification of the multilayer printing structures discussed above is described.

5.1 Measurement of reflectance and transmittance of calligraphy pieces

A calligraphic work of the Chinese character was used as the reproduction target. An artist with excellent brushwork skills was employed and ink having slightly thinner density than the standard density was used to emphasize the difference in reflectance and transmittance with changes in brushwork.

Reflectance and transmittance of the calligraphy piece were measured in the environment shown in Fig. 6. White LED lighting was used as the light source for reflectance measurement. To uniformly illuminate the surface of the subject, the light source was used to illuminate a diffuser and then the diffuser illuminates evenly the subject. The intensity of light reflected from the subject was digitized using a camera, and the reflectance was derived using values from

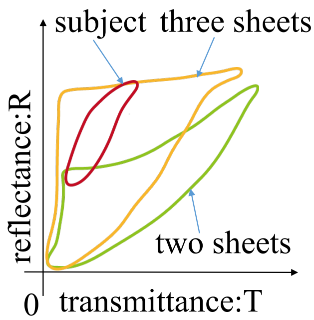


Fig. 8: Comparison of dynamic ranges.

a diffuse reflected standard with known reflectance that was measured under the same environmental conditions. Transmittance was measured using a flat panel display showing white grayscale value over the entire screen to illuminate the subject from the back with a fixed intensity. The subject was placed on a flat panel display in a dark room, and the intensity of the transmitted light was measured using the camera. Transmittance of the subject was derived using the brightness of a gray scale pattern slide with known transmittance that was measured under the same environmental conditions. Figure 7 shows images of reflected and transmitted light from the digitized calligraphy piece.

5.2 Measurement of gradation pattern and evaluation of dynamic range improvement by blank sheet insertion

Reflectance and transmittance measurements of the gradation pattern of a multilayer printing structure were carried out under the same environmental conditions as the calligraphy pieces.

Figure 8 shows the dynamic ranges of the measured subject (calligraphy piece) and the gradation patterns of two-sheet and three-sheet multilayer printing structures. The distribution of the subject shows that there are regions with different transmittance even though the reflectance is the same, which implies that one type of printing pattern alone cannot reproduce the subject sufficiently. In addition, use of two sheets of printing paper cannot cover most of the dynamic range of the subject. Reflectance and transmittance was then measured for a gradation pattern from a three-sheet multilayer printing structure in which a blank sheet was inserted between two printed sheets. The transmittance decreased somewhat, but the reflectance increased as a whole, and the dynamic range of the subject was almost entirely covered. The coverage ratio using two sheets was only 33%, but the increase to three sheets resulted in a 98% coverage ratio; therefore, the insertion of a blank sheet improved the dynamic range, entirely covering that of the subject.

5.3 Verification of multilayer structure effectiveness

In this section, the effectiveness of combining patterns printed on different sheets of paper to reproduce reflectance and transmittance is discussed. We evaluate the reproducibility of the reflectance and transmittance of an object using the proposed method in which different patterns are printed on two sheets of paper and a single sheet using a printer. Three

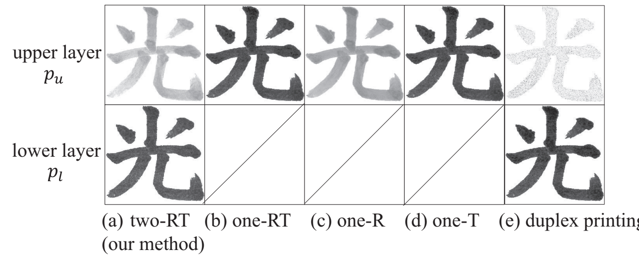


Fig. 9: Calculated ink density of upper and lower layers.

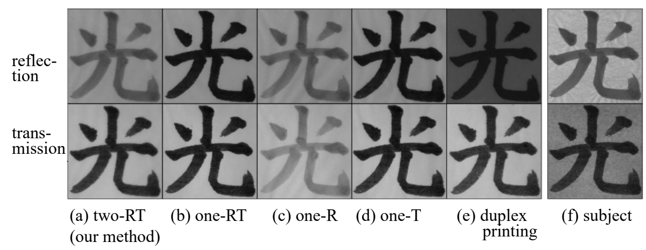


Fig. 10: Reproduced images of reflectance and transmittance.

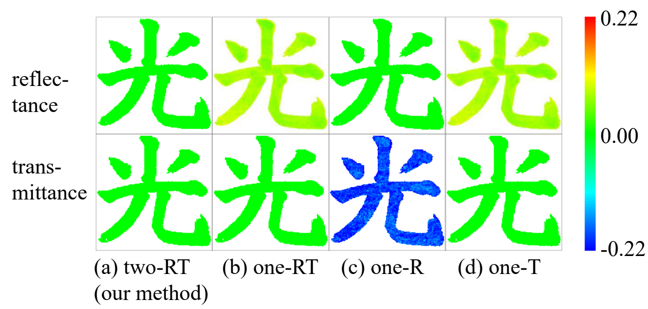


Fig. 11: Discrepancy maps of reflectance and transmittance. Since we focused on a region on the line of a letter, a background region is shown as white.

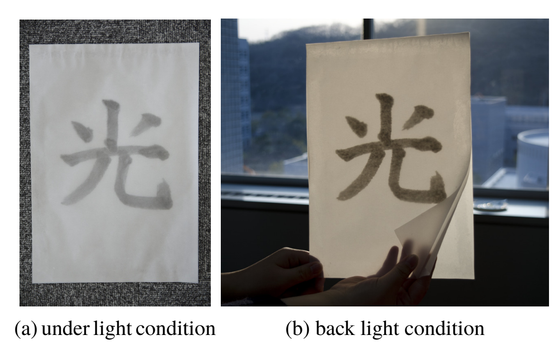
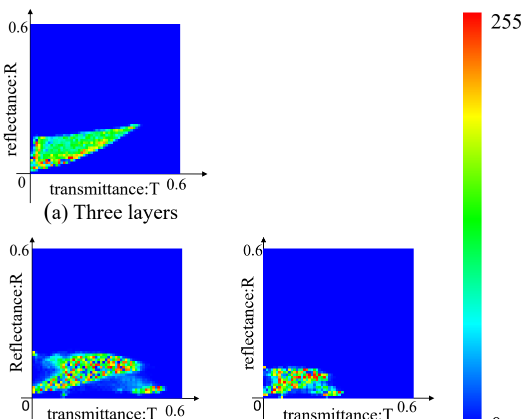


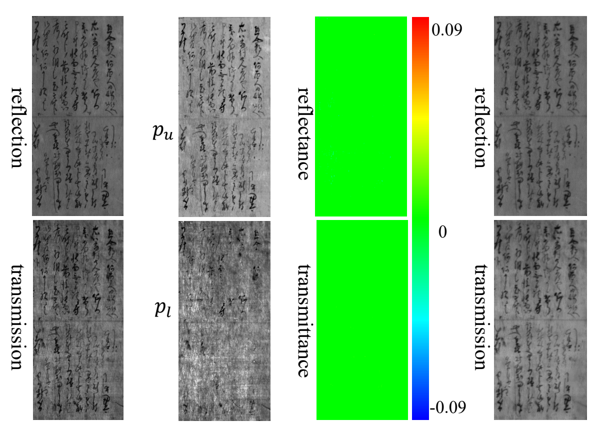
Fig. 12: Reproduction with created replica when (a) put down and (b) held up.

Fig. 13: Old documents to create the replica.



(a) Three layers (b) Old document before compression (c) Old document after compression

Fig. 14: Comparison of dynamic ranges.



(a) sample1 measurement (b) Result using LUT (c) Discrepancy distribution (d) Created replica

Fig. 15: Old documents for replication testing.

sheets of printing paper were used in both cases, to ensure the same number of stacked sheets of printing paper were used. A blank sheet was inserted between two printed sheets in the proposed method, while the printed sheet was used as the top sheet and two blank sheets were positioned below in the latter. In addition to these methods, in which three sheets of printing paper were stacked, a naive method to create replicas was also adopted, in which patterns were printed on both sides of a sheet of printing paper.

Reflectance and transmittance data were obtained by measurements using three gradation patterns created with the above methods. The reflectance and transmittance measurement results of the gradation patterns were saved as lookup tables, from which the ink concentrations needed to reproduce optical properties at given points can be obtained by reverse lookup. The upper and lower layer grayscale values were determined based on Eq. (1), above. This method is denoted as "two-RT", below.

Determination of the ink density of one sheet used for comparison was accomplished by using following function. Consideration of both reflectance and transmittance is denoted as "one-RT", obtained by as follows:

$$\operatorname*{argmin}_{p_u} \left(|R - r_1(p_u)| + |T - t_1(p_u)| \right). \tag{3}$$

When only reflectance is considered (one-R), the following equation is used:

$$\operatorname*{argmin}_{p_u} |R - r_1(p_u)|. \tag{4}$$

When only transmittance is considered (one-T), the following is used:

$$\operatorname*{argmin}_{p_u} |T - t_1(p_u)|. \tag{5}$$

Here, $r_1(p_u)$ and $t_1(p_u)$ are the reflectance and transmittance, respectively, of a multilayer printing structure in which only one sheet is printed. The ink density when both sides are printed, or duplex printing, is determined based on Eq. (1), where p_u and p_l correspond to the ink density on the front and back sides of the object, respectively.

Figure 9 shows p_u and p_l values obtained with the respective equations. The lower layer grayscale values were not controlled in (b)–(d), and hence are not shown in the figure. The upper and lower layer grayscale values in (e) are those printed on the front and back sides, respectively.

Multilayer printing structure replicas were actually created based on the obtained ink density patterns. Figure 10 shows the reflected and transmitted light that were measured under environmental conditions similar to those shown in Fig. 6, and a pseudo-color representation of the discrepancy between subject and replica is shown in Fig. 11.

These results show that the proposed method (Fig. 11 (a)) excesses in reflectance and transmittance over all of Fig. 11 (b)–(e). The discrepancy of at least one of reflectance or transmittance is relatively large in Fig. 11 (b)–(e), suggesting that reproduction of both reflectance and transmittance with a printed sheet is difficult, while using multiple printing patterns is effective.

Figure 12 shows calligraphy piece replicas created using the above methods in a natural environment. The "feel" of the original calligraphy piece is reproduced both when strongly reflected light is visible from the replica placed on the floor, and when there is effect of transmitted light from the replica

Table 1: Coverage ratio of dynamic range.

method	sample1	sample2	sample3
two layers	46%	64%	14%
three layers	92%	84%	80%
four layers	60%	39%	60%

held in one's hands.

5.4 Evaluation of reproduction of old documents

Replicas of three privately owned old documents (Fig. 13) were conducted to evaluate the reproduction of actual old documents. The reflectance and transmittance values were obtained after measuring reflected and transmitted light of the old documents under environmental conditions shown in Fig. 6.

Three types of multilayer printing structures were prepared, in which zero, one, and two blank sheets were inserted (two, three, and four layers, respectively) and the dynamic ranges were compared with those of the target old documents. Table 1 shows the dynamic range coverages. Insertion of one blank sheet (three layers) gave the best results for all samples, although the coverage was not necessarily sufficient. The dynamic range for sample 1 in Fig. 13 was compressed with scaling of $\alpha_r = 0.7$ and $\alpha_t = 0.6$ for reflectance and transmittance, respectively, to fit into the dynamic range that can be reproduced with a multilayer structure with one blank sheet inserted. Obtained histograms are shown in Fig. 14 . The histogram of the old document after compression (Fig. 14 (c)) has a smaller dynamic range compared to before compression (Fig. 14 (b)), but covers the dynamic range of the multilayer printing structure with one blank sheet inserted (Fig. 14 (a)).

Figure 15 shows results of reproduction using compressed reflectance and transmittance. Figure 15 (a) shows images of the reflected and transmitted light of an old document prior to compression, and Fig. 15 (b) shows the upper and lower layer grayscale values (p_u and p_l, respectively) obtained using the lookup table. Figure 15 (c) represents the discrepancy distribution of the reproduced results, showing that both reflectivity and transmissivity were reproduced almost completely after compression except very small region on the top of the reflectance discrepancy distribution. The digitized reflected and transmitted light of the actually created replica are shown in Fig. 15 (d). The contrast levels in the reflected and transmitted light images of replica (d) were slightly lower than those of the original (a). Visual inspection of the created replica showed significant discrepancies at folds and creases. Effects of folds and creases were out of the scope of this work, but their consideration is a necessary task when reproducing the "feel" of ink paintings.

5.5 Verification of light blur

In this study, simultaneous reproduction of reflectance and transmittance was accomplished using a multilayer printing structure in which multiple printed sheets were stacked.

Table 2: Relation between pitches of resolution charts and normalized cross-correlation values.

pitch[mm]	0.12	0.24	0.6	1.2	2.4	6.0	12.0
NCC	0.18	0.79	0.95	0.96	0.96	0.96	0.97

Table 3: The selected numbers of black felt.

	two-RT	one-RT	one-R	one-T	total	score
two-RT	—	18-4	13-9	19-3	50	0.55
one-RT	4-18	—	4-18	6-16	14	−0.55
one-R	9-13	18-4	—	20-2	47	0.52
one-T	3-19	16-6	2-20	—	21	−0.52

However, stacking of printed sheets may result in blurring of transmitted light and decrease in spatial frequency properties. Therefore, evaluations were conducted to determine the extent of light blur in the investigated multilayer printing structures.

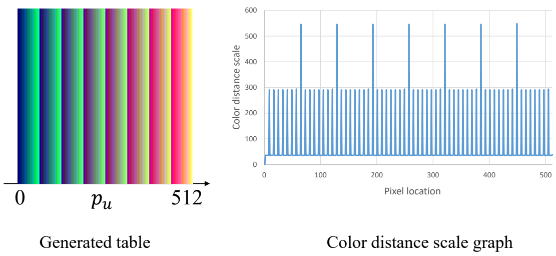
Stripe patterns of various densities were printed on printing paper to prepare resolution charts. Transmitted light images were obtained by direct imaging of a resolution chart and a simulated multilayer printing structure in which a resolution chart was stacked together with two blank printing sheets. A high value of the normalized cross-correlation (NCC) of these digitized images indicated very little blur, and a low value corresponded to decreased spatial resolution from blur. A resolution chart was printed with black solid lines in one of seven different pitches (0.12 mm, 0.24 mm, 0.6 mm,1.2 mm, 2.4 mm, 6 mm, 12 mm), and the calculated NCC values are shown in Table 2.

The spatial resolution of the replica created under the environmental conditions of our experiment was 0.25mm per pixel, which corresponds to NCC of 0.80 based on linear interpolation of two neighboring samples according to Table 2. Therefore, some effects, although limited, from blur were found under the conditions of our experimental environment. However, increase in created replica resolution was expected to rapidly increase the effect of blur. Printing of sharp patterns that cancel out the effect of blur in the multilayer printing structure is one possible remedy, but its verification is a future task.

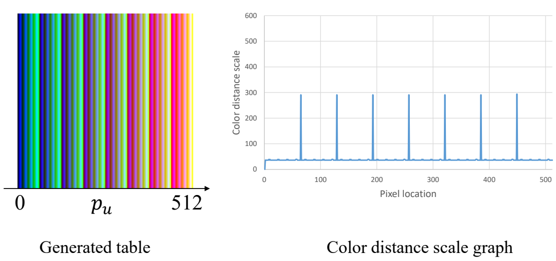
5.6 Qualitative evaluation experiment

To clarify the appropriateness of replicas created using the proposed method from the viewpoint of human perceptions, qualitative evaluation experiments based on the naked eye were conducted on two-RT (proposed method), one-RT, one-R, and one-T replicas based on Thurstone's pair comparison method.

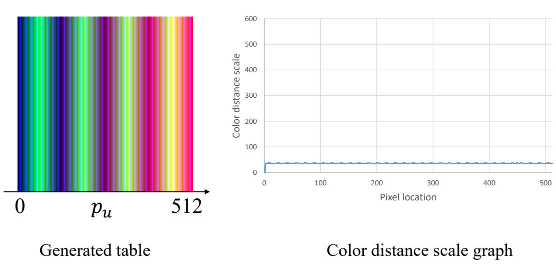
Two arbitrary replicas and the original ink painting that was to be reproduced were placed on a black felt foundation to simulate a standard ink painting exhibit. Participants chose the replica that they considered to be closer to the original. This experiment was conducted for all combinations of four replicas (${}_4C_2 = 6$ combinations) and the responses of the participants were recorded. Table 3 shows the results for



(a) Creation process 1

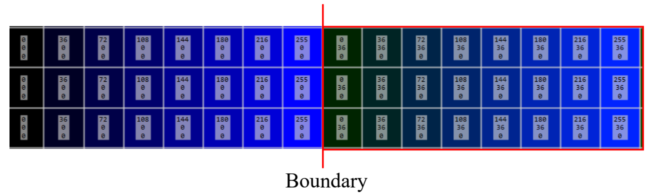


(b) Creation process 2



(c) Creation process 3

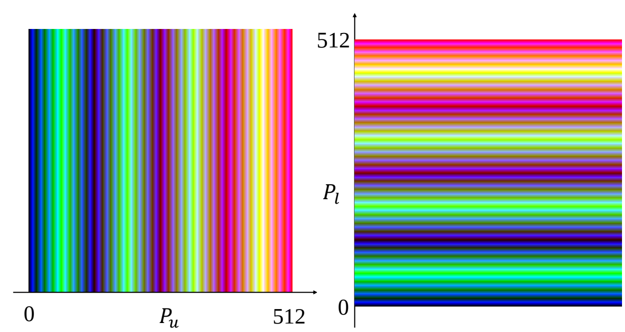
Fig. 16: Process of lookup table creation.



(a) Before inversion

(b) After inversion

Fig. 17: Changes with inversion.



(a) Upper layer color (b) Lower layer color

Fig. 18: Color gradation pattern.

22 participants aged in their 20s.

As an example, an entry of “13-9” in this table, which appears in the row for two-RT and column for one-R, means that 13 participants chose two-RT and 9 chose one-R. Scale values were obtained from the total number of selections, and two-RT was most frequently selected. The difference in scale value from second-best one-R was small, but 13 out of 22 selected two-RT in a direct comparison. As a result, the proposed method was shown to be effective to some extent.

6. Creating replicas that simultaneously reproduce reflectance and transmittance in color

This section expands the proposed method from grayscale to red, green, and blue to create colored replicas. This will make possible reproduction of color fading caused by aging of ink paintings in addition to reflectance and transmittance.

6.1 Creating color lookup tables

The reflected and transmitted light to be reproduced were measured in the environment shown in Fig. 6. A Sigma SD15 camera containing a Foveon X3 image sensor with three color sensing layers (red, green, and blue) was used as the imaging equipment to prevent degradation of spatial resolution of each color compared to Bayer imaging equipment, which use a filtered CCD sensor. The target was an old document owned by the authors and images are shown in Fig. 19 (a).

The lookup table needed to be reconstructed for colored images to achieve sample-based three-color reproduction. The tone of each color (red, green, and blue) was limited to eight tones (0, 36, 72, 108, 144, 180, 216, and 255) to limit the number of total combinations. Therefore, the number of combinations of ink densities of the upper and lower layers was $8^3 \times 8^3 = 262,144$. In the grayscale case, some shifts in reference position, for instance from errors in measurement, did not result in huge discrepancies in ink density, because the lookup table was prepared as a monotonous gradation from white to black. However, in the three-color scale, if 8^3 color pixels are randomly positioned in the lookup table, small shifts in reference position will result in huge errors in color. Therefore, the gradation pattern to be used in the

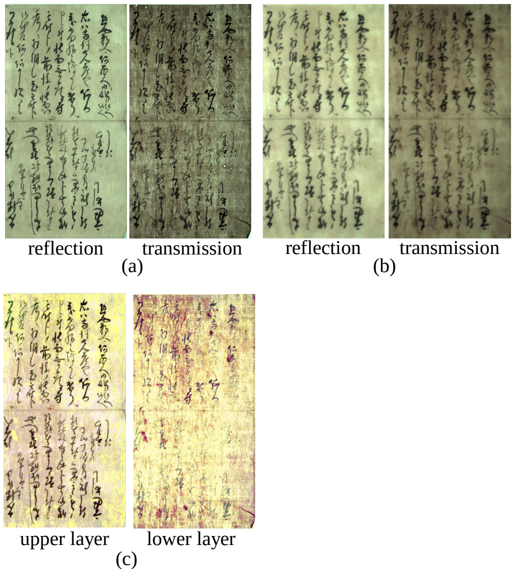


Fig. 19: Example of color reproduction of an old document. Exterior view of (a) old document and (b) replica, and (c) upper and lower layer colors of prints in the multilayer printing structure.

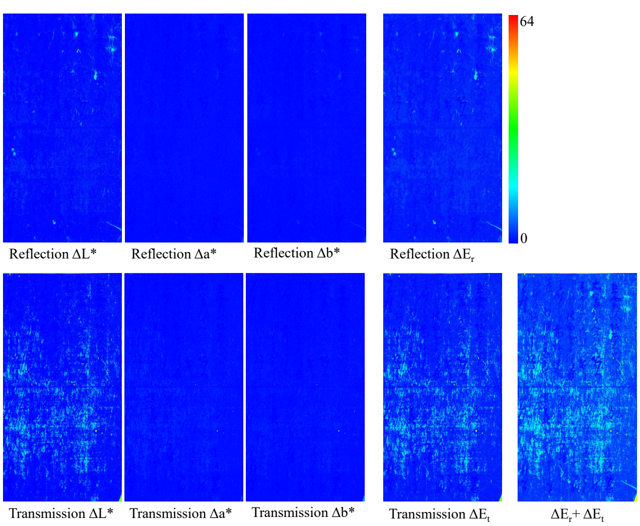


Fig. 20: Discrepancy distribution when reproducing an old document.

lookup table for color reproduction were arranged such that the color distance scale $\Delta L = |\Delta R| + |\Delta G| + |\Delta B|$ was the same between neighboring pixels. Slight shifts in reference pixel position, for instance from inappropriate decoding, would not result in extreme shifts from the correct pixel in this setting.

A naive choice in color order results in fluctuation in color distance scale, as shown in Fig. 16 (a), and is prone to large errors in the reference pixel value. To keep the color distance scale in the lookup table to a constant value, columns of eight pixels were formed and even columns were vertically inverted, because the color distance scale between

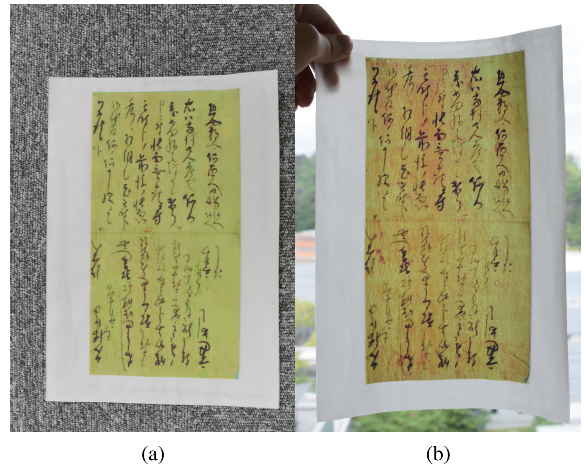


Fig. 21: Reproduction with created color replica when (a) put down and (b) held up.

the rightmost pixel of odd columns and neighboring leftmost pixel of even columns were not uniform. This inversion gradually made the color distance scale uniform, as shown in Fig. 16 (b). Figure 17 also indicates that the color distance scale became uniform on the basis of change in pixels before and after inversion. Creating 64 pixel-wide columns in the lookup table of Fig. 16 (b) and vertically inverting even columns resulted in a gradation pattern with uniform color distance scale, as shown in Fig. 16 (c). The images of reflected and transmitted light from multilayer printing structures in which these gradation patterns were stacked (Fig. 18) were measured.

6.2 Discrepancy function of colors and replica creation

The color difference in CIE-L*a*b* space was used as a discrepancy function based on human perception to determine the upper and lower layer colors of the color replica, and upper and lower layer colors (p_u and p_l, respectively) that minimize the discrepancy function were obtained.

Figure 19 (b) shows the light images of reflectance and transmittance of the multilayer printed structure replica, and Fig. 19 (c) provides the upper and lower layer color printing patterns of the multilayer printed structure. Distributions of ΔL, $\Delta a*$, and $\Delta b*$ of reflected and transmitted light as well as distributions of the reflected light color difference ΔE_r, transmitted light color difference ΔE_t, and $\Delta E_r + \Delta E_T$ are shown in Fig. 20. Observation of the created replica revealed good reproduction of locations where characters were written and the color of the Japanese paper. However, unevenness of fibers in the Japanese paper could not be sensed when transmitted light was observed. This is also evident from the discrepancy distribution in Fig. 20.

The above shows that the proposed color multilayer printing structure can reproduce characters drawn in ink and color of Japanese paper, but room for improvement exists in reproduction of fiber unevenness found in transmitted light.

Figure 21 shows the color replica created with the above method in an actual environment.

7. Conclusions

In this study, a method was proposed to create an optical replica that reproduces both reflectance and transmittance of an ink painting by printing different patterns onto multiple sheets of paper and then stacking them. We showed through experiments that using a single printed sheet, which is the conventional method, causes difficulty when attempting to reproduce both the reflective and transmissive qualities of the original, but that this becomes possible with the proposed method using two printed sheets. In addition, two methods to achieve the reproducibility of dynamic ranges of reflectance and transmittance to those of the target ink painting were proposed, namely compression of the dynamic range of the target to be reproduced and increasing the dynamic range by inserting a blank sheet between two printed sheets. Also, we expanded our method to create colored replicas. The accuracy is not enough compared with our gray scaled replicas, but it is still meaningful to generate colorful replicas which preserve the original appearance. The proposed method used a printer, and therefore could not reproduce dynamically changing contents, for instance animation. However, reproduction of static contents such as ink paintings is easily accomplished, and the reproduced replica can be held in hand and freely observed by anyone. This research can be thought as a new form of computer graphics expression, because reproduction of overall sensory impression, or "feel", of objects that were previously only shown on a screen, is now applied to actual fabrication. Compression of the dynamic range was conducted with different scaling coefficients for reflectance and transmittance, but its validity needs to be evaluated from the viewpoint of human perception. Also, the dynamic range in the proposed method was found to be too narrow when reproducing the reflectance and transmittance of old documents. This issue was resolved by scaling the dynamic range such that reproduction by a multilayer printing structure is possible, but establishing methods to further expand the dynamic range is necessary. One possibility is optimization of printing paper, for instance by using tracing paper that is thinner and more transparent, or clear film. We need to conduct reproduction and verification experiments on old documents again after sufficiently expanding the dynamic range.

Acknowledgments

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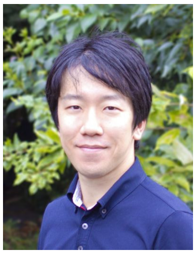

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