The authors propose a method of producing virtual mezzotint using a physics-based rendering approach. Mezzotint is a traditional copperplate printing technique. An important characteristic is its gradations from black to white. This is acquired in three phases during the plate-making process, i.e., by roughening, scraping, and burnishing. Numerous dots and burrs are created with a rocker in the roughening phase over the entire surface of the copper plate to obtain black areas in the print. The burrs are removed in the second phase with a scraper to yield halftones. The plate surface is finally polished with a burnisher in the last phase to produce the white areas. A method of simulating these phases and physical phenomena is discussed in this paper to make mezzotint enjoyable even for beginners and children. Zigzag-stroke patterns and paraboloidal-dot models are applied to the rocker to simulate the roughening phase. Reducing and smoothing models are applied to the scraper and burnisher to simulate the scraping and burnishing phases. The feasibility of the proposed method is demonstrated by observing and comparing actual and virtual plate surfaces with determined patterns and actual pieces of handcrafted work.

1. Introduction

Mezzotint\textsuperscript{6,8} was developed as a traditional technique of copperplate printing\textsuperscript{10,15} in the mid-17th century. It has the potential to acquire various gray tones, as shown in Fig. 1. It was utilized industrially to republish portraits and duplicate oil paintings in the 19th century. It has achieved recognition for its artistic qualities since the early 20th century, and has hence become known as a fine-art technique.

There are various kinds of copperplate printing techniques apart from mezzotint, and these generally consist of four processes: (a) making the plate, (b) applying ink to it, (c) wiping it, and (d) pressing it, as shown in Fig. 2. Tasaki, et al. has already proposed a method of non-photorealistic rendering (NPR)\textsuperscript{21} in the computer graphics (CG) field to simulate drypoint, which is another copperplate printing technique. Mezzotint is categorized as a kind of the plate making methods in a more limited sense. While a drypoint print consists of many black lines achieved by incising the plate with a hard sharp point, an important characteristic of mezzotint is its smooth gradations from black to white. The plate’s surface needs to go through three phases to acquire the effect of mezzotint, i.e., roughening, scraping, and burnishing. A comb-like steel tool called a rocker is used in the roughening phase to create many dots on the plate. Each dot has burrs that are raised above the surface of the plate. As these dots and burrs hold ink, the resulting print has a black effect, as shown in Fig. 1 (roughened portions). The burrs are removed in the second phase, using another steel tool called a scraper to control the remaining ink around them. The scraped portions produce a halftone effect in the print, as shown in Fig. 1 (scraped portions). If the artist wants lighter tones, as shown in Fig. 1 (burnished portions), the plate is polished using another steel tool called a burnisher. Although these three phases result in a variety of gray tones, they are very onerous and laborious processes even for mezzotint specialists. For example, it takes about 30–40
days to roughen a $50 \times 65$ cm plate. Therefore, the purpose of this research was to make mezzotint more safely and easily available with CG techniques to a much broader range of novices and children who were not specialists. It was therefore important to simulate the roughening, scraping, and burnishing procedures and the physical phenomena of mezzotint to render images that looked like mezzotint prints.

An approach using a physical model corresponding to the actual mezzotint process is proposed in this paper. Zigzag-stroke patterns and paraboloidal-dot models are introduced in the roughening phase to simulate the manipulation of the rocker and its interaction with the plate. A reducing model is applied to simulate the scraping phase and a smoothing model is applied to simulate that for burnishing. The feasibility of the proposed method is demonstrated by observing and comparing actual and virtual plate surfaces with determined patterns and pieces of handcrafted work. The actual pieces were made by one of the authors, who is also a copperplate-printing specialist.

2. Related Works

NPR has been extensively studied\(^5\),\(^17\),\(^18\) in CG research fields, and it has been applied to various applications such as CG movies. NPR techniques have attracted many viewers and CG researchers and most of these have focused on line-art illustrations\(^3\),\(^24\), oil paintings\(^7\), and watercolors\(^2\). A few research groups have concentrated on copperplate printing as another way of synthesizing artistic NPR images. Some studies on simulating engraving, which is a method of plate making for copperplate printing have been reported by Leister\(^9\), Ohno, et al.\(^11\), and Pnueli, et al.\(^14\). These studies have been based on the fact that engraved lines can be approximated only with lines, and they have focused their strategies on how to generate line patterns geometrically by imitating the look of engraving. Ostromoukhov\(^12\) described another method of synthesizing a print from an engraving based on a plate model. Although the model could imitate engraved lines, it did not simulate the actual process. Tasaki, et al. reported a model-based method of virtual engraving\(^20\) based on the idea of a method of virtual drypoint, which will be discussed in Section 3.

The impression given by mezzotint prints is similar to the effect of halftoning or dithering. Ostromoukhov, et al.\(^13\) described a method of dithering by using various space-filling curves and Delauney triangulation, and they claimed that their results looked like a mezzotint print in terms of appearance. These previous methods of copperplate printing used an appearance-based rendering (ABR) approach. Tasaki, et al. proposed a pipeline for modeling and rendering virtual drypoint, which is also a method of plate making for copperplate printing, with a physics-based rendering (PBR) approach\(^21\). It is expected to attain a similar appearance to an actual drypoint print with physical fidelity to the original because the PBR method simulates the production procedure and the physical phenomena that occur during the actual drypoint process. The inputs to incise the virtual plate with their method are stroke data because a drypoint print can be represented with lines. In contrast, the target of this research was mezzotint, which can be represented with areas. Therefore, the inputs for scraping and burnishing the virtual plate are region images. Tasaki, et al. also proposed methods of virtual mezzotint\(^22\),\(^23\). They introduced a model of random dots for the roughening phase, an evenly reducing model for the scraping phase, and an evenly smoothing model for the burnishing phase. Their observation and analysis were insufficient because they used a book-scanned mezzotint print as a reference in their experiments. We improved on the studies done by Tasaki, et al.\(^22\),\(^23\) by using detailed comparisons and experiments with actual handcrafted mezzotint prints produced by a copperplate-printing specialist to obtain the virtual mezz-
zotint results.

Sourin\textsuperscript{16}) proposed a functionally based representation to express the shape of the plate. Its shape with the method we propose is expressed with a height field. It is a convenient and straightforward way of simulating the shape of the plate and the behavior of the ink in all the production processes. Bosch, et al. proposed a method of rendering scratches\textsuperscript{1} on the surface of metals by computing the Bidirectional Reflection Distribution Function based on measurements of actual scratches. As their model would also be useful for our system to render the shape of the plate’s surface more accurately, we intend to use it in future work.

3. Physical Models of Mezzotint

The pipeline for virtual copperplate printing proposed by Tasaki, et al.\textsuperscript{21)–23)} is illustrated in Fig. 3. It is based on intermediate expressions that uniformly deal with various kinds of devices as input. The pipeline can synthesize a virtual copperplate print from an intermediate once it can be created from the inputs. The plate-making process for mezzotint consists of three phases: roughening, scraping, and burnishing. This section describes improved models for the three phases. Wiping and pressing models are also described.

Note that the shape of the copperplate surface is expressed with a height field:

\[ P = \{ p(X) \mid X = (i, j) \in \mathbb{N}^2 \}. \]  

3.1 Physical Model for Roughening

A rocker in the shape of a comb with many small teeth, as shown in Fig. 4 (a), is placed on the copper plate, and it is rocked zigzag or back-and-forth. It produces many microscopic dots over the entire surface of the plate. A zigzag-stroke pattern, which consists of many strokes, as shown in Fig. 5, was introduced to simulate rocking. This was based on the same concept as the mark-making primitive proposed by Sousa, et al.\textsuperscript{17)}. Each stroke is defined by \( Q_i \) and \( Q_{i-1} \) in this paper. The \( i \)-th \( Q \) is expressed as:

\[ Q_i = X + v_i \frac{V}{|V|} + w_i \frac{W}{|W|}, \]  

\[ v_0 = 0, \]  

\[ v_i = v_{i-1} + N(\mu_v, \sigma_v^2), \]  

\[ w_i = (-1)^i N(\mu_w, \sigma_w^2), \]  

where \( X \) represents the beginning point for the zigzag pattern, \( V \) is its direction and length, and \( W \) specifies the direction orthogonal to \( V \).

\( N(\mu_v, \sigma_v^2) \) stands for the normal distribution of the stride for each stroke with average \( \mu_v \) and standard deviation (SD) \( \sigma_v \). \( N(\mu_w, \sigma_w^2) \) also stands for the normal distribution of the width of each stroke. Actual rocking is repeated longitudinally, latitudinally, and diagonally in two directions, until the plate surface is evenly filled.

\[ \]
with a vast amount of dots.

The rocker during each stroke makes a number of dots according to $N_t$, which is engraved on the side of the actual rocker and indicates the number of teeth per inch ($\#65$, $\#85$, and $\#100$ are commonly used). $N_t$ is also utilized for the virtual rocker to calculate how many dots will be incised by a stroke. When the rocker produces a dot, the plate material rises around it, and this is called a burr. These dots and burrs hold the ink during the applying ink, wiping, and pressing processes. The shape of a dot incised by a virtual-rocker tooth is illustrated in Fig. 6. This is based on the paraboloidal model for drypoint $^{21}$, and is expressed as:

$$h = ar^2 - b \quad (0 \leq r \leq r_i),$$

$$a = \frac{D}{R}, \quad b = DF + f, \quad r_i = \frac{b}{a},$$

where $D$ indicates the depth and $R$ indicates the radius of an incised dot. Their values were measured against a digital photo of an actual rocker ($N_t = 85$), as shown in Fig. 7. $f$ represents fluctuations in manual force, and follows a normal distribution, $N(0, \sigma_f^2)$. Although $F$ represents the rocker pressure, this has not yet been considered and is fixed at the present stage. Burrs formed around dots are also expressed with the drypoint model. The domain of a burr, $(r_i < r \leq r_b)$, is calculated with the law of volume conservation, which assumes that the entire incised volume becomes burred.

Equation (7) is approximately applied under a 2-D cross-sectional area, and $r_b$ is determined from this equation.

$$\int_0^{r_b} (ar^2 - b) \, dr = 0,$$

$$r_b = \frac{3b}{a} = \sqrt{3}r_i. \quad (8)$$

### 3.2 Physical Model for Scraping

A scraper that looks like a blade, shown at the top of Fig. 4 (b), is utilized to cut the burrs away during the actual scraping phase. A lighter gray tone appears in the resulting print when the plate is scraped more because the burrs hold less ink. Scraping in the virtual phase is expressed by reducing the plate heights, as illustrated in Fig. 8. This operation is completed on the basis of the region image, which specifies the area and the level to be scraped with an integer value. The highest plate value, $p_{\text{max}}$, in region $R = \{X = (i, j) \in \mathbb{N}^2\}$ is calculated as:

$$p_{\text{max}} = \max_{X \in R} p(X). \quad (9)$$

Scraping the plate is expressed by reducing the plate’s height, $p(X)$, from $p_{\text{max}}$ close to 0, as:

$$p'(X) = \min\{p(X), \alpha p_{\text{max}} f_s(X)\}, \quad (10)$$

where $\alpha$ is the reduction rate. There are irregularities during the actual scraping because of fluctuations in hand movements. The function, $f_s(X)$, is a fractal component that expresses these irregularities. Although there are many kinds of fractal algorithms, function $f_s(X)$ is generated by a method of two-dimensional midpoint displacement $^4$ with SD $\sigma_{fs}$; this is one of the most straightforward fractal methods. These calculations with Eqs. (9) and (10) are iterated several times as specified by the region image.

### 3.3 Physical Model for Burnishing

If the artist wants a highlight effect, a spoon-shaped burnisher, shown at the bottom of
The average plate height in region $R$ is calculated as:

$$\bar{p} = \frac{1}{N} \sum_{X \in R} p(X),$$

(11)

where $N$ is the number of plate cells in $R$. Burning the plate’s surface is expressed by reducing the plate’s height from $p(X)$ close to $\bar{p}$ as:

$$p'(X) = (1 - \beta f_b(X))p(X) + \beta f_b(X)\bar{p},$$

(12)

where $\beta$ is the smoothing rate. The function, $f_b(X)$, is a fractal component to express irregularities in burning, in the same way as the scraping operation mentioned above, and it is generated by a method of two-dimensional mid-point displacement with SD $\sigma_b$. These calculations with Eqs. (11) and (12) are iterated several times as specified by the region image.

3.4 Physical Model for Wiping Process

The wiping process proposed by Tasaki, et al. briefly introduced in this section where the user wipes a virtual cloth interactively to determine the amount of the ink remaining on the surface of the virtual copperplate. The system pre-calculates the lowest height curve for wiping the cloth based on a simple spring model before interactive operation occurs. This calculation is iterated until the values are converged.

3.5 Physical Model for Pressing Process

The ink-spreading phenomenon occurring under heavy pressure during the pressing process was approximated with a random walk model with the former methods. The spreading ink affects the resulting print due to linear interpolation between the paper and the ink according to the latter’s thickness. Two improved models were applied to the pressing process. The first was an ink-spread model that produced many unexpected white dots in the resulting print. A simple Gaussian filtering model with a mask size of $N_g$ was utilized to separate problems from artifacts.

The second model was for paper deformation. Tasaki, et al. stated that a characteristic of copperplate prints was deformation in the paper sheets according to the plate’s shape during the pressing process under heavy pressure, and this affected their appearance. They investigated the properties of the paper after the pressing process in detail. They then concluded that these properties could be achieved by expressing the deformation with a combination of macroscopic and microscopic shapes. The macroscopic shape of the paper represents deformation that is caused by the plate’s shape as:

$$S(X) = -(p(X) + P_{th}),$$

(13)

where $P_{th}$ stands for the thickness of the copper plate. The microscopic shape, $T(X)$, represents slight bumps on the paper’s texture as:

$$T(X) = T_\sigma(X)T_{\max}(1 - D(X)), $$

(14)

where $T_\sigma(X)$ is a bump map expressing irregularities on the paper’s surface, and this is generated with a fractal method of two-dimensional mid-point displacement. $T_{\max}$ represents the amplitude of the bumps. $D(X)$ denotes the ratio of deformation:

$$D(X) = \frac{S(X) + P_{th} - S_{\text{low}}}{S_{\text{high}} - S_{\text{low}}},$$

(15)

where $S_{\text{high}}$ and $S_{\text{low}}$ are values that restrict the effect of microscopic deformation near the plate’s surface. Finally, the shape of the deformed paper, $S'(X)$, is expressed as:

$$S'(X) = S(X) + T(X).$$

(16)

This gives the virtual print a slight shading effect, which can be observed in an actual mezzotint print.

4. Experiments and Discussion

The physical models of mezzotint proposed in Section 3 were implemented on a computer. Table 1 lists the values of the parameters used.
Table 1  Values of parameters used in models.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius of incised dot, $R$</td>
<td>64.9 $\mu$m</td>
</tr>
<tr>
<td>Depth of incised dot, $D$</td>
<td>37.1 $\mu$m</td>
</tr>
<tr>
<td>SD for depth of incised dots, $\sigma_R$</td>
<td>2.0 $\mu$m</td>
</tr>
<tr>
<td>Number of teeth on rocker, $N_t$</td>
<td>80 $^\dag$</td>
</tr>
<tr>
<td>Width of zigzag stroke, $\mu_w$</td>
<td>17.5 $\mu$m $^\ddagger$</td>
</tr>
<tr>
<td>SD for zigzag stroke width, $\sigma_w$</td>
<td>1.0 $\mu$m $^\ddagger$</td>
</tr>
<tr>
<td>Stride of zigzag stroke, $\mu_v$</td>
<td>0.3 $\mu$m $^\ddagger$</td>
</tr>
<tr>
<td>SD for zigzag stroke stride, $\sigma_v$</td>
<td>0.1 $\mu$m</td>
</tr>
<tr>
<td>Reduction rate for scraping, $\alpha$</td>
<td>0.9 $^\ddagger$</td>
</tr>
<tr>
<td>SD for scraping fluctuations, $\sigma_{ib}$</td>
<td>0.01 $^\ddagger$</td>
</tr>
<tr>
<td>Smoothing rate for burnishing, $\beta$</td>
<td>0.9 $^\ddagger$</td>
</tr>
<tr>
<td>SD for burnisher fluctuations, $\sigma_{fb}$</td>
<td>0.01 $^\ddagger$</td>
</tr>
<tr>
<td>Plate thickness, $P_{th}$</td>
<td>800 $\mu$m</td>
</tr>
<tr>
<td>Amplitude of paper bumps, $T_{max}$</td>
<td>30 $\mu$m</td>
</tr>
<tr>
<td>Higher limit for deforming ratio, $S_{high}$</td>
<td>$-127 \mu$m</td>
</tr>
<tr>
<td>Lower limit for deforming ratio, $S_{low}$</td>
<td>128 $\mu$m</td>
</tr>
<tr>
<td>Mask size for Gaussian filter, $N_g$</td>
<td>170 $\mu$m</td>
</tr>
</tbody>
</table>

The dagger $^\ddagger$ indicates that the value has been determined by actual measurement, and the others have been determined by experiments. The double dagger $^\ddagger$ indicates that the value depends on the artist.

in the experiments. The dagger $^\ddagger$ indicates that the value has been determined by actual measurement, and the others have been determined by trial and error. The double dagger $^\ddagger$ indicates that the value depends on the artist because this has been determined based on his or her work. Therefore, these values are stable while simulating touches by the same artist. The plate has a resolution of 2,540 dpi to represent the shape of the incised dots in detail. For example, an 8.5 $\times$ 6.6 cm image is composed of 8,500 $\times$ 6,600 pixels. Various 3-D images representing plate surfaces rendered with OpenGL are also presented in this section to indicate the flexibility of the proposed method.

A copperplate-printing specialist, who is one of the authors, created two actual mezzotint plates and took prints from them in the first stage of the experiments. The first consisted of systematically determined phantom patterns to confirm the capabilities of the proposed method. The roughening phase is generally repeated until the plate surface is uniformly roughened, and the gray tones are controlled by scraping and burnishing. We therefore concentrated on the effect of scraping and burnishing in the experiments. The second was an actual handcrafted piece of work to demonstrate that the method could be applied to practical use. The intermediate expressions for scraping and burnishing operations in the experiments were displayed with a color bar for better visualization, as shown in Fig. 11 (17 tones in this study).

4.1 Experiment with Predetermined Phantom Pattern

An experiment with a predetermined phantom pattern was first conducted to parametrically indicate how effective the scraping and burnishing operations were. Note that $I_s$ specifies the index for scraping and $I_b$ specifies that for burnishing. These symbols in this section correspond to the ones in Fig. 10. Figure 12 (a) is an actual mezzotint print consisting of 5 $\times$ 5 (= 25) patterns, whose differences are caused by the varying amounts of scraping and burnishing. Although artists can obtain more than 25 gray tones in their work in practice, it is too difficult to produce these patterns with various tones. The usual combination of scraping and burnishing done by copperplate specialists is on the path $(I_s, I_b) = (0, 0) \rightarrow (1, 0) \rightarrow (2, 0) \rightarrow (3, 0) \rightarrow (4, 0) \rightarrow (4, 1) \rightarrow (4, 2) \rightarrow (4, 3) \rightarrow (4, 4)$. Because it is difficult to only control the tones by burnishing, it can produce prints that are unexpectedly light in tone. Almost artists therefore produce most tones only by scraping. However, it is important to use all combinations because the proposed method is based on a PBR approach. We synthesized 17 $\times$ 17 (= 289) patterns for the experiment to interpolate and extrapolate the domain of actual patterns. Figure 12 (b) is a virtual mezzotint selected from 25 patterns obtained from all the results. Its average light tone matches that of the actual one, and the patterns have been tessellated to fit together. The region image for scraping is
Fig. 11  Color bar to indicate scraping and burnishing levels.

Fig. 12  Experimental results with predetermined phantom pattern (original size: 10×10 cm, magnified 0.2 times).

(a) Actual mezzotint  (b) Virtual mezzotint  (c) Region image for scraping  (d) Region image for burnishing

Fig. 13  Surface of actual plate observed through loupe (magnified ×3.5, upper right: ×1.0).

(a) $I_s = 0$, $I_b = 0$  (b) $I_s = 4$, $I_b = 0$  (c) $I_s = 0$, $I_b = 4$  (d) $I_s = 4$, $I_b = 4$

Fig. 14  Surface of virtual plate (magnified ×3.5, upper right: ×1.0).

(a) $I_s = 0$, $I_b = 0$  (b) $I_s = 4$, $I_b = 0$  (c) $I_s = 0$, $I_b = 4$  (d) $I_s = 4$, $I_b = 4$

Fig. 15  Actual printed pattern (magnified ×3.5, upper right: ×1.0).

(a) $I_s = 0$, $I_b = 0$  (b) $I_s = 4$, $I_b = 0$  (c) $I_s = 0$, $I_b = 4$  (d) $I_s = 4$, $I_b = 4$

Fig. 16  Virtual pattern (magnified ×3.5, upper right: ×1.0).
Fig. 17  Comparison of actual and virtual mezzotints using hancrafted work.

Fig. 18  Experimental results with photograph (size: 6.8×6.8 cm, magnified 0.5 times).

Fig. 19  Experimental results with a CG image (size: 3.4×3.4 cm, exact size).
shown in Fig. 12 (c) and that for burnishing is in Fig. 12 (d). Actual and virtual tones can simultaneously be compared in Fig. 10 by tiling up the triangular regions for them. The states of the actual plate’s surface can be observed through a loupe, as shown in Fig. 13. The loupe has an aluminum plate with a square hole in its center and metric scales are arranged around the hole. Figure 14 compares the states of the virtual plate’s surfaces with the actual ones. Figure 15 shows the state of an actual printed pattern and Fig. 16 shows that of a virtual pattern.

4.2 Practical Experiment

The results of a practical experiment using an actual mezzotint are presented in Fig. 17. Its original size in (a) is $8 \times 6$ cm, and it has been trimmed to demonstrate its actual size on this paper. The regions to generate the images for scraping and burnishing in Fig. 17 (c) and Fig. 17 (d) have been manually and subjectively segmented referring to the gray tones of the actual print with image processing software (Adobe Photoshop), and the levels have been defined on the basis of the results of the phantom experiment. A virtual mezzotint work was obtained with the proposed method on this basis, as shown in Fig. 17 (b). Figure 17 (e) shows the state of the actual plate surfaces and Fig. 17 (f) shows that of the virtual after the pressing process. These states can clearly be observed because a slight amount of ink remains on the plate even after cleanup.

4.3 Discussion

The difference in tones caused by scraping and burnishing can be macroscopically seen in the experimental results presented in Fig. 10 and Fig. 12. Differences in touches can be microscopically observed as differences in the maximum and minimum gray levels. The tops of the burrs have been flattened by scraping, and the area interacting with the wiping cloth increases during the wiping process, as shown in Fig. 13 (b) and Fig. 14 (b). However, ink still remains in the incised dots. Therefore, the resulting print is high in contrast, as shown in Fig. 15 (b) and Fig. 16 (b). However, the plate’s surface has been polished by burnishing to refill the burrs into the incised dots, as shown in Fig. 13 (c) and Fig. 14 (c). There is no disproportionate amount of ink in this case as there is in scraping. Therefore, the resulting print is low in contrast, as shown in Fig. 15 (c) and Fig. 16 (c). The virtual print has more contrast than the actual one, comparing the experimental results with the phantom patterns (Fig. 12 (a) and Fig. 12 (b)). A slight oil slick remained on the high-contrast portions after the actual wiping process, and created a half-tone effect in the print. The phenomenon caused by the oil slick has not yet been modeled in the proposed method, and this can be approximated by manually controlling the contrast. As the interface for the virtual-wiping process is poor, the process is done by evenly bearing the virtual wiping cloth down on the plate. The interface should therefore be improved to enable users to intuitively control the amount of wiping. Some highlighted lines can be observed in Fig. 13, especially in Fig. 13 (a). These were caused by the differences in force during rocking. Variations in force during operation have not yet been considered in the proposed method.

The virtual print in Fig. 17 (b) appears similar to the actual one in Fig. 17 (a), compared to the results of the practical experiment, although there is the same problem with contrast. The region images are also not optimized. All the region images used in the experiments were created manually and subjectively. One purpose of the proposed method was to establish a way of simulating the creation of a mezzotint with the region image, i.e., an intermediate expression. Thus, how to make region images fit user or artist sensibilities is a topic for future study. Figure 18 and Fig. 19 have other examples whose region images have been generated by mainly utilizing the ‘Magic Wand Tool’ in Photoshop. The scraping regions to be acquired are first determined according to the required gray tones based on the results mentioned above. The burnishing regions are also determined to emphasize the main objects in the image. This gives some indication of the possibility of automatically applying our method to various kinds of inputs.

The experiments were done with a computer running PowerPC G5 (2.5 GHz and dual CPU) and 2.5 GBytes of memory with C language. It took about 2.5 hours to synthesize the virtual mezzotint (Fig. 17 (b)), i.e., roughening took 88.0 [sec], scraping took 200.3 [sec], burnishing took 173.4 [sec], wiping took 3,723.4 [sec] (about 1 hour), and pressing took 56.3 [sec]. However, it took about 2 weeks to create the actual mezzotint work (Fig. 17 (a)). The proposed method is therefore able to remarkably reduce the time required. However, it still took a long time to
calculate the shape of the wiping cloth, and this is the main bottleneck impeding practical use in the future.

5. Conclusion

A physics-based method of virtual mezzotint was proposed in this paper corresponding to the actual mezzotint process, which consists of three phases: roughening, scraping, and burnishing. A zigzag-stroke pattern and a paraboloidal-dot model were applied to roughen the plate's surface with a virtual rocker. A reducing model was introduced that used a virtual scraper. A smoothing model was introduced to burnish the plate's surface with a virtual burnisher. These models accomplished the effect of gradation, which is an important characteristic of mezzotint. The authors demonstrated the effects of the proposed method by observing and comparing actual and virtual plate surfaces with systematically determined patterns and a practical piece of work that had been created by a copperplate-printing specialist. The synthesis of a virtual mezzotint from an input image was used to demonstrate how scraping and burnishing regions could be used as intermediate expressions.

We intend to improve the model for wiping and pressing processes in future work to take the effect of oil slicks into consideration to acquire better impressions. The coloring model is simply approximated with a linear interpolation between paper and ink colors. It should be improved with various kinds of non-linear methods to acquire more accurate impressions. The wiping process should be improved so that it calculates the shape of the wiping cloth more quickly in practical use. A more accurate method of rendering is required for better visualization. A pressure sensitive stylus to construct a user-friendly interface needs to be utilized to control the amount of scraping, burnishing, and wiping.

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