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Creating a Virtual Wooden Sculpture and a Woodblock Print with a Pressure Sensitive Pen and a Tablet

Shinji MIZUNO[1]*, Daigo KOBAYASHI[2], Minoru OKADA[3],
Jun-ichiro TORIWAKI[4] and Shinji YAMAMOTO[5]

[1]*Information and Media Center, Toyohashi University of Technology, Toyohashi 441-8580, Japan*
[2]*Department of Knowledge-based Information Engineering, Toyohashi University of Technology, Toyohashi 441-8580, Japan*
[3]*Graduate School of Information, Production and Systems, Waseda University, Kitakyusyu 808-0135, Japan*
[4]*School of LifeSystems and Technology, Chukyo University, Toyota 470-0393, Japan*
[5]*School of Computer and Congnitive Sciences, Chukyo University, Toyota 470-0393, Japan*
**E-mail address: mizuno@imc.tut.ac.jp*

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Abstract. In this paper, we present an interactive CG creating system with a pressure sensitive pen and a tablet. This system is based on the virtual sculpting and printing method which are simulations of the real sculpting and woodblock printing. In the virtual sculpting process, the user operates virtual chisels with the pen to sculpt a virtual wooden object which has a 3D shape. The user can control the carving depth and the carving angle to the surface of the object with the pressure applied to the pen. The system can take the change in the hardness of wood that originates from grain and the surface shape. In the virtual printing process, a woodblock print is generated from woodblocks which are created in the virtual sculpting process. The pressure sensitive pen is used to operate a Japanese printing squeegee, Baren (disk-shaped pad). The user can control the thickness of the print by changing the pressure of printing operation. It is possible to synthesize a realistic Ukiyo-e print in the same process with the same carving and printing techniques as creating it in the real world.

1. Introduction

Recent progress of computer technology has made computer graphics (CG) more familiar to anyone, and the chance that general people treat CG has been increasing. Thus, CG creating systems which any users can use without special knowledge of computers and CG are required. Adopting the art creating techniques of the real world in the CG system is one of the most effective solution. It is also useful for synthesizing non-photorealistic images, and many art techniques of the real world are used in such systems. Many real creating methods are simulated in the virtual space such as sculpting and embossing (GALYEAN and HUGHES, 1991; SOURIN, 2001), clay modeling (MASSIE and SALISBURY, 1994; MAENO *et al.*, 2004), painting on a 3D surface (JOHNSON *et al.*, 1999), oil and watercolor painting with virtual brushes (SAITOH and NAKAJIMA, 1999; BAXTER *et al.*, 2001; XU *et al.*, 2003), pen and ink illustration (SALISBURY *et al.*, 1994), copperplate printing (TASAKI *et al.*, 2004), and so on.

As one of these systems, we have developed the virtual sculpting and printing system (MIZUNO *et al.*, 1999, 2000a, 2000b). This system enables the user to experience and enjoy interactive sculpting and woodblock printing in the virtual space. Our system aims that it useful not only for beginners like children but also artists who have actual techniques of wooden sculpting and woodblock printing. For the virtual sculpting scheme, we implemented an interactive modeling technique to form a solid object with carved surfaces by carving a virtual workpiece with a virtual chisel as we do in the real world. We also proposed the virtual printing scheme that is a method to synthesize a woodblock print by simulating its real process. The user creates a monochrome print and a multicolored print like Ukiyo-e by using virtual items such as woodblocks, a paper sheet, ink, and a Baren (disk-shaped pad) in the system (MIZUNO *et al.*, 2001, 2002).

In the former virtual sculpting, the user used a mouse to operated a chisel. It is difficult to give parameters of the carving depth and the carving angle to the surface only with a mouse, and it was necessary to input them with the keyboard before carving. It was exact and useful for industrial products, but it was different from real carving operation and not so suitable for artistic works. To solve this problem, other hardware devices which can input parameters besides a 2D position, such as a 3D mouse or a haptic device are useful (GALYEAN and HUGHES, 1991; MASSIE and SALISBURY, 1994).

A pressure sensitive pen and a tablet is one of the most popular pressure sensitive hardware devices, and it is often used for 2D drawing (SAITOH and NAKAJIMA, 1999; XU *et al.*, 2003). In generating a 3D sculpture and a printing woodblock, the chisel mainly moves in the 2D space with various power. We consider that a pressure sensitive pen and a tablet are suitable for simulating virtual carving operation with chisels in our system (MIZUNO *et al.*, 2003), and develop a new user interface using this hardware device. A user operates a virtual chisel with a pressure sensitive pen on a tablet instead of using a mouse. The pressure value of the operation is converted to parameters of the carving depth and the carving angle dynamically.

Using the new interface, the system can take into the concept of the hardness of the workpiece. In the real wooden sculpting, surface shapes of sculpture and grain of wood often cause a change of the hardness. There is an important wood carving technique which uses the change of hardness based on the surface shape. The grain is an important factor to express a characteristic style of the work, and the artists change the carving style according to the grain in creating works. We propose a method to express the difference of the hardness of a virtual wooden workpiece that results from the shape of the surface and the grain of the wood, by analyzing the shape and the texture of the workpiece. We also develope a new interface for the virtual printing to operate a Baren, that is a disk-shaped pad and used to press the paper sheet against the printing block. Changing the pressure of operating a Baren is one of important techniques to make gradations on the printed image in real printing, especially for Ukiyo-e. There are specialists for printing process in making Japanese Ukiyo-e. The pressure sensitive pen is suitable to realize this technique in our virtual printing scheme.

2. Outline of Virtual Sculpting and Virtual Printing Scheme

2.1. Virtual sculpting

In our virtual sculpting, an original workpiece and several virtual chisels are prepared in a virtual space. The original workpiece is a curved surface polyhedron that is a simple shape with a CSG (Constructive Solid Geometry) expression. Each virtual chisel is defined by an ellipsoid, a cube and a cylinder, and the shape of a carved solid object is also expressed with a CSG expression. As carving operations, the user can remove or attach

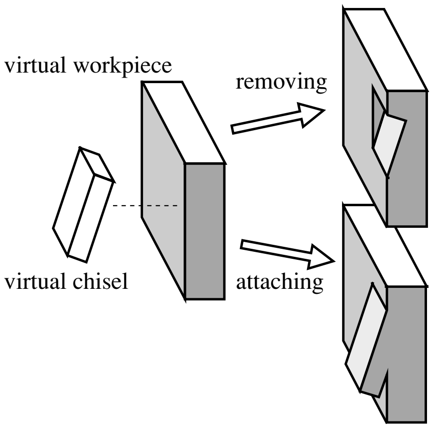


Fig. 1. Deformation by removing and attaching the shape of a virtual chisel.

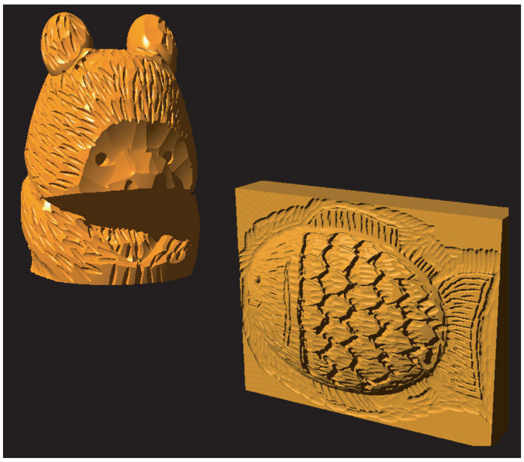


Fig. 2. Examples of virtual sculptures created by our virtual sculpting scheme.

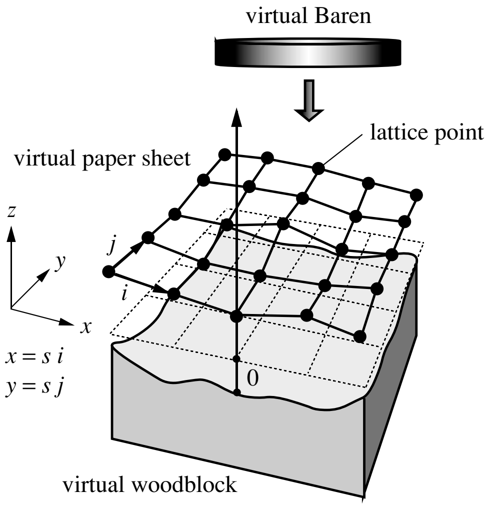


Fig. 3. A printing block, a paper sheet, and a Baren in the virtual space.

pieces of virtual chisels from or to the workpiece. Removing/attaching is an operation which subtracts/adds the pieces (Fig. 1). By performing these operations repeatedly, the user can form a complex solid object. There are various styles of wooden sculpture, and our system realizes to create virtual sculptures which have clear carving marks with chisels on the surface (Fig. 2).

The user carves a virtual workpiece displayed on the screen directly, and then the workpiece is deformed at once. To deform the workpiece in real time, a list of intersecting points along with each viewing line on the screen is generated. The list of intersecting points is suitable for interactive deformation in virtual sculpting (MIZUNO *et al.*, 1999). They are revised each time when each carving operation is done or when the viewpoint is changed. A carving record of the user's operations or a logical formula of the primitives constructs the shape of the solid sculpture.

2.2. Virtual printing

Using a board as a workpiece in the virtual sculpting, a printing block can be generated. In the printing stage, a user synthesizes a printing image from the printing woodblock, a paper sheet, a Baren (disk-shaped pad), and ink in the virtual space (Fig. 3).

A virtual paper sheet is expressed as a 2D lattice. Each lattice point can move only in the direction of the z-axis. The virtual paper sheet is put on the virtual woodblock, and the operation of the virtual Baren decreases the distance from the printing block to the virtual paper sheet interactively. This distance decides the wetness of the ink at each point on the paper sheet, and an image is synthesized one after another (Fig. 4). A multicolored woodblock print can be synthesized by using several virtual woodblocks with each color of ink (MIZUNO *et al.*, 2002). It is a simulation of the real woodblock printing process, and the image by our virtual printing scheme is also similar to real woodblock prints.

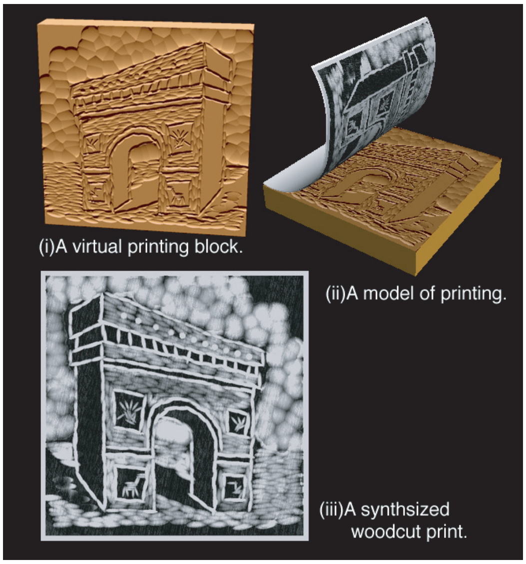


Fig. 4. Examples of virtual woodblock prints.

3. The New User Interface for Virtual Sculpting

3.1. The position of the virtual chisel in the space

We aim the operation of virtual sculpting to be simple and similar to the real sculpting. We use the dragging operation for carving a wooden object with a chisel. The user chooses one from the virtual chisels of different widths and shapes, and drags on the virtual workpiece displayed in the screen. One carving operation is done with one dragging. The length of the chisel, the point on the surface of the workpiece, and the rotation on the normal vector at the point can be obtained from the position and the direction of dragging (Fig. 5). The operation only with a mouse cannot give the parameters of the carving depth and carving angle to the surface, so the user must input these values before carving operation. A virtual chisel is put at the position decided in this way, and this chisel deforms the workpiece at once.

3.2. Carving with a pressure sensitive pen

The user must use a mouse and a keyboard together to operate a virtual chisel in the former system. In order to realize the closer operation to the real carving without using a keyboard, we developed the new user interface using a pressure sensitive pen and a pressure sensitive LCD tablet. The user can give the values of the carving depth: d, and the carving angle to the surface: θ, dynamically only with the pen. The user drags on the LCD tablet with the pen to carve the virtual workpiece. This is similar to that with a mouse. The pressure applied to the pen is transferred to the carving depth and the carving angle to the

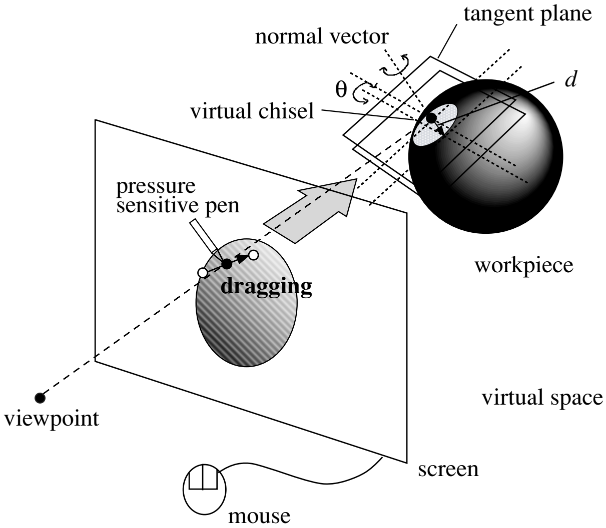


Fig. 5. Placing a virtual chisel on the workpiee.

surface (Fig. 6). The carving depth: d, is decided based on the average of the pressure: p_a, in one carving operation.

$$d = r_z p_a / p_{max}, \tag{1}$$

r_z: the height of the virtual chisel, p_{max}: the maximum sensitive pressure.

The carving angle to the surface: θ, is decided based on the average of the first half pressure: p_f, and the latter half: p_l, in the carving operation.

$$d_{\{f,l\}} = r_z p_{\{f,l\}} / p_{max}, \tag{2}$$

$$\theta = \tan^{-1}\{(d_l - d_f)/0.5l\}, \tag{3}$$

l: the length of the carving operation in the virtual space.

To carve deeply, the user should operate the pen strongly like real operation of a chisel. The transition of the pressure during one carving operation decides the carving angle to the surface.

3.3. Long and curved carving operation

A long curved line can be expressed as connected short straight lines approximately (MIZUNO *et al.*, 2000a). During carving operation, anchor points are put on the carving lines one after another according to the length and the curvature value of dragging. The i-th anchor point: $\mathbf{a}_i$ ($i \geq 2$) is put if it fills the next condition (Fig. 7(a)).

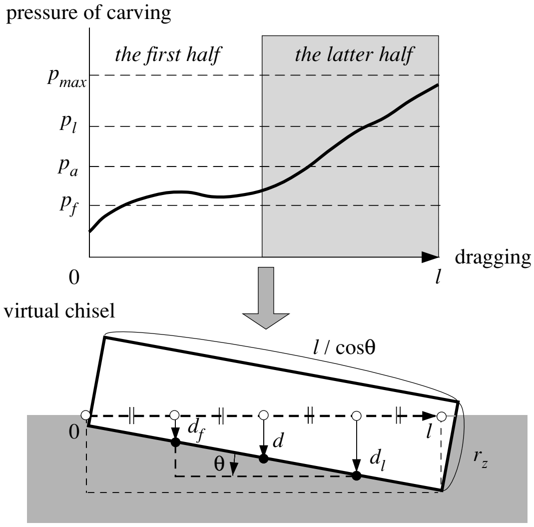


Fig. 6. Getting the carving depth and the carving angle from the pressure applied to the pen between the carving operation.

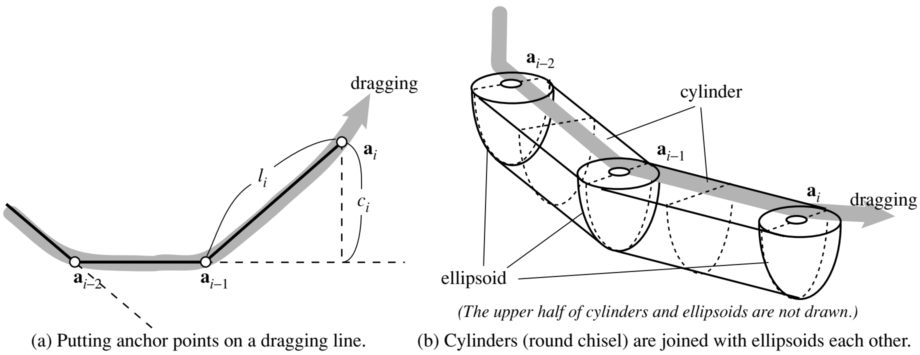


Fig. 7. An example of long and curved carving operation.

$$l_i = |\mathbf{a}_i - \mathbf{a}_{i-1}| > l_{\max} \ \vee \ c_i = \sqrt{|\mathbf{a}_i - \mathbf{a}_{i-1}|^2 - \left\{(\mathbf{a}_i - \mathbf{a}_{i-1}) \cdot (\mathbf{a}_{i-1} - \mathbf{a}_{i-2}) / |\mathbf{a}_{i-1} - \mathbf{a}_{i-2}|\right\}^2} > c_{\max}, \tag{4}$$

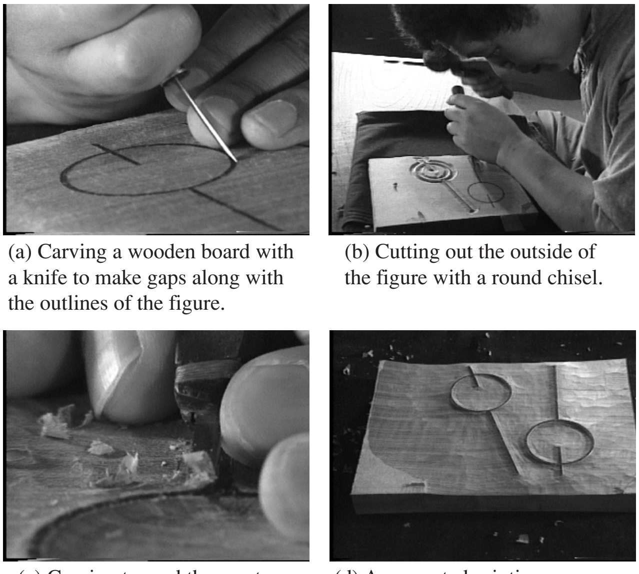
$l_{\max}$: the maximum distance of adjoining anchor points, $c_{\max}$: the maximum displacement of $\mathbf{a}_i$ from the line $(\mathbf{a}_{i-1} - \mathbf{a}_{i-2})$.

The long curved carving line is divided into short straight sub-lines by each anchor point. A virtual chisel is placed on each sub-line with considering the pressure value on the line in the same way as Subsec. 3.2. In order to connect virtual chisel smoothly, ellipsoids or cylinders are placed between each virtual chisel for joints. A long and curved carving mark with a round chisel is expressed by cylinders joined with ellipsoids (Fig. 7(b)). Cubes and ellipsoids are used for triangular chisels, and cubes and cylinders are used for flat chisels.

4. Change of the Hardness of a Virtual Wooden Workpiece

4.1. Analysis of the shape of the surface

Using the new interface we proposed in this paper, the virtual sculpting system can take into the concept of the hardness of the workpiece. In the real wooden sculpting, we sometimes carve the surface thinly and deeply with a knife to make a gap along with the outline of a figure first, and cut out the outside of the figure next. If we carve by moderate power toward the outline, we will feel that the wood is harder at the gap of the outline, and the chisel will stop there. The reason is that a wooden fragment separates from the workpiece when the edge of the chisel arrive at the gap, the edge of the chisel comes out to the exterior of the workpiece, and the whole edge hits the surface of the workpiece again. This technique is called “Kirimawashi” in Japanese (ADACHI), and often used in making reliefs and printing woodblocks for Japanese woodblock prints Ukiyo-e to generate clear



(a) Carving a wooden board with a knife to make gaps along with the outlines of the figure.

(b) Cutting out the outside of the figure with a round chisel.

(c) Carving toward the gap to make the outline clear.

(d) A generated printing woodblock for Japanese Ukiyo-e.

Fig. 8. A technique to generate a clear outline of a figure in making a printing woodblock for Japanese Ukiyo-e.

outline of the figure (Fig. 8). Thus, it is important to realize this technique in the virtual sculpting and the virtual Ukiyo-e printing.

We realize this phenomenon in the system by analyzing the shape of the surface of the virtual workpiece. When the user operate a pressure sensitive pen to operate a virtual chisel, the system searches for a gap at the tip of the virtual chisel by calculating the coordinates of the surface at each pixel on the carving line. The carving mark is stopped automatically when the depth of the gap: d_{gap} fills the following condition (Fig. 9).

$$d_{\mathrm{gap}} < r_z p / p_{\max}. \tag{5}$$

This formula means that the carving operation will be stopped at a gap when the gap is deeper than the position of the tip of the virtual chisel. If the user operates the virtual chisel strongly, the carving mark will cross the gap. Here, although the value of the right-hand side of the formula (5) may differ from the position of the edge of the carving chisel a little, we consider that an exact value is not required for this phenomenon, and it does not matter.

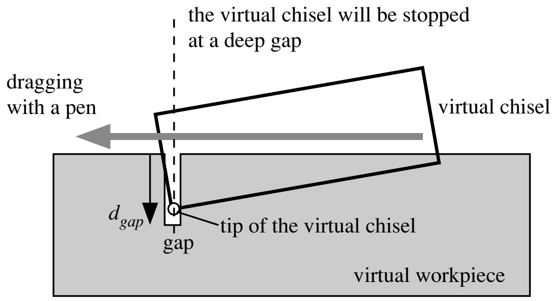


Fig. 9. A method to realize the carving technique Kirimawashi in the virtual sculpting.

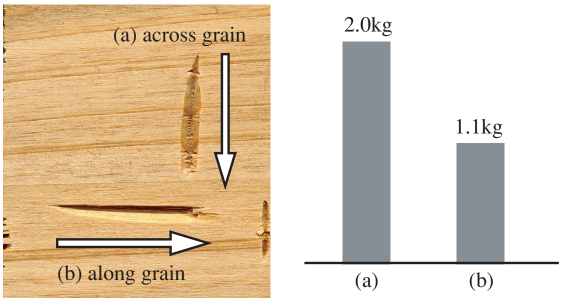


Fig. 10. Comparison of power required for carving a wooden workpiece with a triangular chisel between two carving directions.

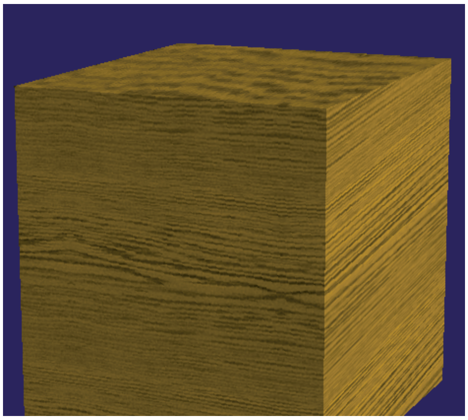


Fig. 11. A grain texture on the virtual workpiece.

4.2. Analysis of grain texture

Grain is produced by the change of the growing speed of a tree with seasons. The portion which grew in autumn has high density of fibers and it is harder than the portion which grew in spring. The color of the portion which grew in autumn is darker than the portion grew in spring. Fibers grow along grain, thus it is easier to carve a wooden workpiece along grain than to carve crossing to grain. When we carve a wooden workpiece with a chisel, the hardness changes with the directions and the positions of carving. In our experiment, the power required to carve a wooden workpiece across grain was about twice the power required to carve along grain (Fig. 10).

In the virtual sculpting system, a wooden workpiece has grain expressed with a texture. The grain texture is a 3D image (700 × 700 × 700) which is synthesized by extending a gray value 2D grain image (Fig. 11). The portions grew in autumn have low values and the portions grew in spring have high values. We realize the change of the hardness of the virtual wooden workpiece by analyzing the grain texture. When the user drags a pressure sensitive pen on the virtual workpiece to carve it, a carving area is decided based on the dragging line (Fig. 12). The system calculates the average of gray value and the frequency of crossing fibers in the carving area, and decides the hardness of the virtual workpiece in the carving area.

The average of the gray value: g_a, shows the ratio of the portion of the wood that grew in spring and autumn. The virtual wooden workpiece becomes harder as the average becomes low. To analyze the frequency of crossing fibers of wood, we set a threshold of gray value: g_t. The system counts the number of the gray value crossing the threshold on the carving line: n, and calculates the frequency: f. Considering the average of the gray value and the frequency of crossing fibers in the carving area, the carving depth: d is redefined by the following expression.

$$f = n/l, \tag{6}$$

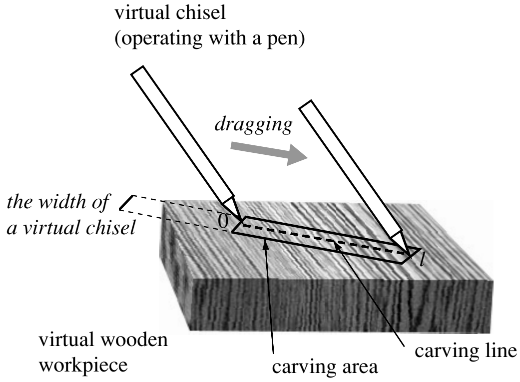


Fig. 12. A carving line and a carving area.

$$d = r_z p_a / p_{max} * C_0 (g_a / g_{max}) * C_1 \{(f_{max} - f)/f_{max}\}, \tag{7}$$

g_{max}: the maximum gray value of the texture ($0 < g_a < g_{max}$), f_{max}: the maximum frequency of crossing fibers ($0 < f < f_{max}$), C_0, C_1: coefficients (change with the kind of wood).

To calculate the carving angle to the surface: θ, the formula (2) is redefined as the formula (8).

$$d = r_z p_{(f,l)} / p_{max} * C_0 (g_{a(f,l)} / g_{max}) * C_1 \{(f_{max} - f_{(f,l)})/f_{max}\}, \tag{8}$$

$$\theta = \tan^{-1}\{(d_l - d_f)/0.5l\}, \tag{3}$$

g_{af}, g_{al}: the first/latter half of the average of gray values in the carving area, f_f, f_l: the first/latter half of the frequency of crossing fibers on the carving line.

In these method, the virtual sculpting system can take in the concept of the hardness of wooden workpieces caused by the shape of the surface and the grain.

5. Virtual Printing with a Pressure Sensitive Pen

In the real woodblock printing, the user uses a Baren (disk-shaped pad) to push the paper sheet against the printing block. The pressure applied to the Baren can control the printed image and generates gradations of color and density. This technique is very important to synthesize a Japanese print Ukiyo-e (SATO, 1999), and the printing process is done by specialists.

In the virtual printing, a virtual Baren is defined with a disk that has a same shape as the real one. The virtual paper sheet is placed on the printing block and the virtual Baren is placed on the paper sheet. The z coordinate of the bottom of the Baren is determined based on the average value of the z coordinates of the lattice points under the Baren, z_{Ba} (Fig. 13). Lattice points under the Baren which have z coordinates larger than that of the Baren are

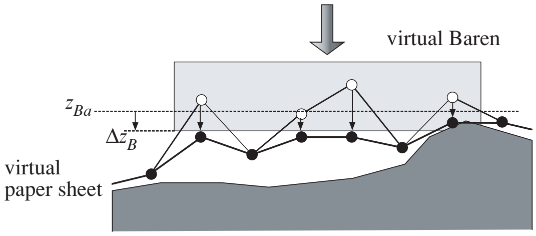


Fig. 13. Movement of lattice points of the virtual paper sheet by operating a virtual Baren.

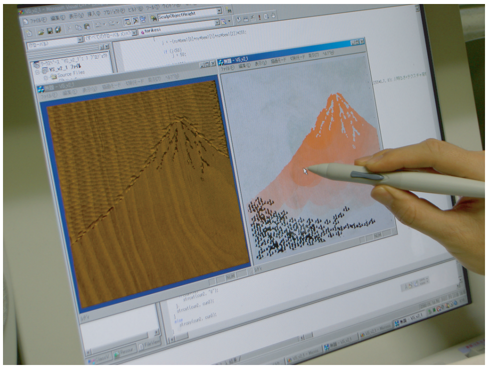


Fig. 14. The virtual sculpting system (the left window), and the virtual printing system (the right window) with a pressure sensitive pen.

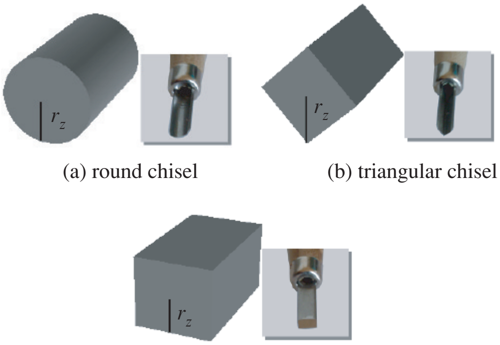
considered to be pushed. They are moved to the bottom of the Baren as far as they do not cave in the printing block. As the user operates the Baren repeatedly, the paper sheet approaches the surface of the virtual printing block gradually.

The displacement value Δz_{B} in Fig. 13 expresses the pressure of the virtual Baren. In the former system, a mouse is used to operate the virtual Baren, and the value Δz_{B} is fixed. The user decides the density of the print only by changing the frequency of operation in each region. This is not similar to the real printing, and it is difficult to generate smooth graduations on the printed image.

We develop a new user interface to operate the virtual Baren with a pressure sensitive pen and a tablet. In this user interface, the value of Δz_{B} is decided based on the pressure applied to the pen in printing operation.

$$\Delta z_{\mathrm{B}} = \Delta z_{\mathrm{Bmax}} p / p_{\mathrm{max}}, \tag{9}$$

Δz_{Bmax}: the maximum displacement of the z coordinate of the virtual Baren, p: the pressure applied to the pen at the point, p_{max}: the maximum sensitive pressure.



(a) round chisel (b) triangular chisel

(c) flat chisel and knife

Fig. 15. Virtual chisels used in the virtual sculpting system, and real chisels corresponding to each virtual chisel.

The more the user applies pressure to the pen in operating a virtual Baren, the closer the virtual paper sheet approaches to the virtual woodblock, and the deeper the woodblock prints an image with the virtual ink. Not only the frequency of the operation, but also the pressure of the operation can change the wetness of the ink printed on the paper sheet.

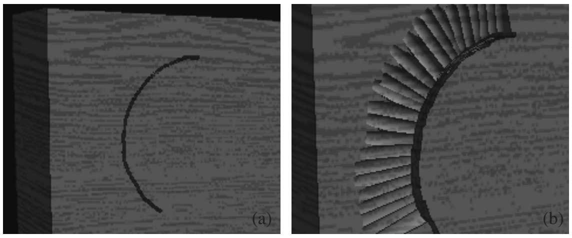
6. Experiments

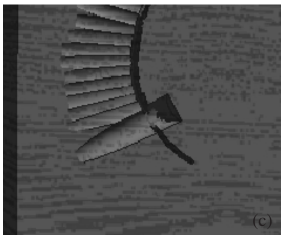
We implemented the virtual sculpting and printing system on a Windows PC (Pentium 4, 3.0 GHz) with a pressure sensitive pen and a LCD tablet (Wacom CintiQ C-1700SX). The sensitivity of the pressure of the tablet (the maximum sensitive pressure) is 512 levels. Figure 14 shows the overview of the system. The resolution of the window for an image is 700×700. We prepared four kinds of virtual chisels each of them corresponds to a real chisel (Fig. 15). The coefficients C_0 and C_1 in the formula (7) and (8) are determined experientially by carving a wooden workpiece with a chisel actually.

In the sculpting process, we confirmed that the carving depth and the carving angle to the surface changed with the pressure of the operation. Using a LCD tablet, it is possible to carry out direct operation to the object displayed on the screen. In this system, the user can carve a virtual workpiece interactively and create a virtual 3D object only with the pen as if carving it in the real world. Figure 16 shows virtual reliefs created in the system with a pressure sensitive pen by one of authors. A triangular chisel and a round chisel were used to create them. In creating the virtual relief (a), the outline of the hand is carved deeply and widely by high pressure operation, and wrinkles are carved shallowly by low pressure. Decorations around the hand are carved with tilt to the surface by changing the pressure between carving operation. The virtual relief (c) is created by long and curved carving operations with triangular and round chisels. It is possible to sculpture in the curve while changing pressure. In the former system, the user had to change the parameters of carving depth and carving angle to the surface before carving. Now the user can change these parameters directly by changing the pressure of carving operation, and it is similar to the real carving operation. Delicate adjustment of carving was difficult as expected.

(a) A hand. (b) From a sculpture on the wall of the building of the British Musium. (c) A sunflower

Fig. 16. Virtual reliefs created in the virtual sculpting system with a pressure sensitive pen.





(a) Making a gap with a virtual knife on the surface of the virtual workpiece.
(b) Carving toward the gap with a virtual round chisel. If the user operates a pen with moderate pressure, carving marks will be stopped at the gap automatically.
(c) If the user operates a virtual chisel too strongly, a carving mark will cross the gap like the carving operation in the real world.

Fig. 17. The Kirimawashi technique to carve a clear outline of a figure in the virtual sculpting.

Figure 17 shows the performance of the Kirimawashi technique in virtual sculpting. A user makes a gap on an outline with a virtual knife first, and, carves with a virtual round chisel toward the outline next. The system searches for a gap on the carving line during the operation. If the operating pressure is moderate and the tip of a virtual chisel is over the bottom of the gap, the carving operation is stopped automatically. Thus, the same technique as Kirimawashi becomes possible, and it is easy to carve a clear outline. If operating a virtual chisel too strongly, the carving operation is not stopped because the tip of the chisel is under the bottom of the gap and the carving mark crosses the gap as the real carving operation. We experimented the change of the hardness of the virtual wooden workpiece coming from the grain. For example, when the user drags the pressure sensitive pen to carve

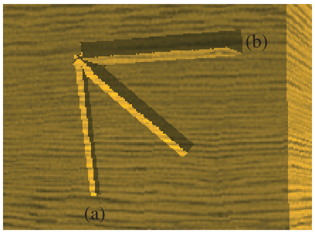
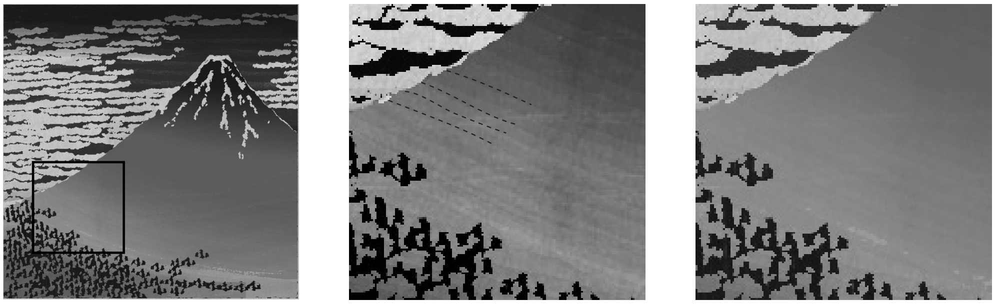


Fig. 18. Carving a virtual workpiece with a grain texture in three directions by the same pressure using a triangular virtual chisel. The carving mark across grain (a) is slighter than the carving mark along grain (b).



(a) An example of a virtual print.

(b) Printed with a mouse as changing a parameter of the pressure value. Unwelcome edges are produced.

(c) Printed with a pressure sensitive pen in the proposed method.

Fig. 19. Comparison of printing results.

the virtual wooden workpiece across the grain, the user must operate the pen with higher pressure than to carve along the grain (Fig. 18). When the user carves the hard portion of the workpiece, the pressure of operation became higher unconsciously. That is, the user can feel the change of the hardness of the workpiece through the pressure sensitive pen in our method. However, it was difficult to express extremely hard wood (but it can be carved) because of the specification of the pen and the tablet.

In the printing process, the user can generate smooth gradations (Fig. 19(c)) by changing the pressure that was difficult in the former user interface (Fig. 19(b)). This improvement is effective in synthesizing Ukiyo-e with our virtual printing system.

Figure 20 shows an experiment of creating Ukiyo-e with our system by one of authors who is not a specialist of Ukiyo-e. It was difficult to create woodblocks for Ukiyo-e by hand, and they were created with the automatic carving method (MIZUNO *et al*., 2000b). Here, using the new system, the user could create five virtual woodblocks for each color with the same technique of Kirimawashi to carve clear outlines of the figure. A little gradation was attached to the background of the woman in the printing process by changing the pressure of operating a virtual Baren. Thus, our system is useful for digital archives of the process of creating Ukiyo-e.

(a) A real Japanese Ukiyo-e created by Kitagawa Utamaro.

(b) A virtual printing woodblock for the green part carved by one of the authers.

(c) A virtual printing woodblock for the black part carved by one of the authers.

(d) A virtual Ukiyo-e printed with three virtual printing woodblocks.

(e) A virtual Ukiyo-e printed with five virtual printing woodblocks.

Fig. 20. Carving virtual woodblocks and printing a virtual Ukiyo-e using same techniques of real Ukiyo-e creation.

7. Conclusions

In this paper, we developed a new user interface with a pressure sensitive pen and a tablet for the virtual sculpting and printing system to make the operation more similar to the real sculpting and the real printing.

In the virtual sculpting, the pressure applied to the pen is used to decide the carving depth and carving angle to the surface as real carving operation. The new interface enabled the system to consider the concept of the hardness of the virtual workpiece in carving operation. We proposed methods to change the hardness of the workpiece by analyzing the shape of the surface and the texture added to the workpiece. The pressure sensitive pen does not have a pressure feedback function, but the user can feel the hardness of the virtual workpiece in these methods. In the virtual printing, the pressure is used to decide the pressure of operating the virtual Baren.

By these improvement, the operation of our system is closer to the real sculptures and woodblock prints, and the system became more useful for beginners of computer graphics. Artists of sculptures and woodblock prints can use their carving and printing techniques in this system too.

In order to realize our plan of digital archives of the process of creating Ukiyo-e, we must have artists or experts of Ukiyo-e use our system and to receive advice. Moreover, we are going to consider use of devices other than a pressure sensitive pen and a tablet.

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REFERENCES

ADACHI [The Adachi Institute of Woodcut Prints—UKIYO-E], www.adachi-hanga.com

BAXTER, W., SCHEIB, V., LIN, M. and MANOCHA, D. (2001) DAB: Interactive haptic painting with 3D virtual brushes, *ACM Computer Graphics (Proc. of SIGGRAPH 2001)*, pp. 461–468.

GALYEAN, T. and HUGHES, J. (1991) Sculpting: An interactive volumetric modeling technique, *ACM Computer Graphics (Proc. of SIGGRAPH '91)*, pp. 267–274.

JOHNSON, D., THOMPSON, T. V., KAPLAN, M., NELSON, D. and COHEN, E. (1999) Painting textures with a haptic interface, *Proc. of IEEE Virtual Reality '99*, pp. 282–285.

MAENO, K., OKADA, M. and TORIWAKI, J. (2004) An interactive and intuitive deformation system for free formed curved surface, *The Journal of the Society for Art and Science*, **3**(2), 168–177.

MASSIE, T. H. and SALISBURY, J. K. (1994) The phantom haptic interface: A device for probing virtual objects, *Proc. of ASME International Mechanical Engineering Congress and Exhibition*, pp. 295–301.

MIZUNO, S., OKADA, M. and TORIWAKI, J. (1999) An interactive designing system with virtual sculpting and virtual woodcut printing, *Computer Graphics Forum (Proc. of EUROGRAPHICS '99)*, **18**(3), pp. 183–193, 409.

MIZUNO, S., OKADA, M. and TORIWAKI, J. (2000a) Virtual sculpting and virtual woodblock printing as a tool for enjoying creation of 3D shapes, *Forma*, **15**, 29–39.

MIZUNO, S., KASAURA, T., OKOUCHI, T., YAMAMOTO, S., OKADA, M. and TORIWAKI, J. (2000b) Automatic generation of virtual woodblocks and multicolor woodblock printing, *Computer Graphics Forum (Proc. of EUROGRAPHICS 2000)*, **19**(3), pp. 51–58, 521.

MIZUNO, S., OKADA, M., YAMAMOTO, S. and TORIWAKI, J. (2001) Japanese traditional printing "Ukiyo-e" in a virtual space, *Forma*, **16**, 233–239.

MIZUNO, S., OKADA, M., TORIWAKI, J. and YAMAMOTO, S. (2002) Improvement of the virtual printing scheme for synthesizing Ukiyo-e, *Proc. of 15th International Conference on Pattern Recognition (ICPR 2002)*, pp. 1043–1046.

MIZUNO, S., KOBAYASHI, D., OKADA, M., TORIWAKI, J. and YAMAMOTO, S. (2003) Virtual sculpting with a pressure sensitive pen, *Proc. of SIGGRAPH 2003 Sketches and Applications*.

SAITOH, S. and NAKAJIMA, M. (1999) 3D physics-based model for painting, *SIGGRAPH '99 Sketches, Conference Abstracts and Applications*, p. 226.

SALISBURY, M. P., ANDERSON, S. E., BARZEL, R. and SALESIN, D. H. (1994) Interactive pen-and-ink illustration, *ACM Computer Graphics (Proc. of SIGGRAPH '94)*, pp. 101–108.

SATO, M. (1999) Masterpieces of six great Ukiyo-e artists, *Hiraki Ukiyo-e Fundation*.

SOURIN A. (2001) Function based virtual embossing, *The Visual Computer*, **17**(4), 258–271.

TASAKI, D., MIZUNO, S. and OKADA, M. (2004) Virtual drypoint by a model-driven strategy, *Computer Graphics Forum (Proc. of EUROGRAPHICS 2000)*, **23**(3), pp. 431–440.

XU, S., LAU, F. C. M., TANG, F. and PAN, Y. (2003) Advanced design for a realistic virtual brush, *Computer Graphics Forum (Proc. of EUROGRAPHICS 2003)*, **22**(3), pp. 533–542.