High-quality Resolution Conversion Method for Halftone Images using Bifluency Interpolation

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***Abstract*—This paper proposes a new resolution conversion method for halftone images. Recently, smartphone or tablet PC has become widespread. When viewing comics on mobile devices as e-books, image resolution conversion is required, because there are various resolution devices. If a resolution of a comic image is reduced with conventional resolution conversion methods using interpolating functions such as bicubic interpolation, moiré that leads to deterioration in image quality is generated because of a halftone that has periodic structures included in comic images. In this paper, we propose a resolution conversion method for halftone images which preserve a periodic structure of original images. Experiments show that a moiré is not generated with our proposed method, and the method is superior in subjective image quality and computational time to the conventional bicubic interpolation.**

I. Introduction

Recently, as the popularity of smartphone or tablet PC, the opportunity to view comics as e-books on portable devices has increased. When viewing comics on mobile devices, image resolution conversion is required because of distribution of various resolution devices in market.

The methods using an interpolating function such as nearest-neighbor, bilinear, bicubic, and Lanczos interpolation [1][2] have been conventionally used to convert image-resolution. However, if resolution of a comic image is reduced with the conventional resolution conversion methods using an interpolating function, a moiré that leads to deterioration in image quality is generated in a resolution-converted image, because a comic image, which is binary and has halftones, simulates continuous tone imagery. Therefore our goal is to propose a high-quality resolution conversion method for halftone image that does not generate any moirés.

If conventional resolution conversion methods using interpolating functions are used, one cycle pattern of an original halftone image might not correspond to that of a resolution-converted image. In this case, the periodic structure of the original image collapses, and a different pattern that means moiré is generated in the resolution-converted image. To propose a high-quality resolution conversion method for halftone images, it is necessary to preserve a periodic structure of an original image. Thus, we focus that halftone images are composed of periodic array of one cycle pattern. In this paper, we propose a method generating one cycle pattern of a resolution-converted image from that of an original image, and composing a resolution-converted image by arranging it periodically. When generating one cycle pattern of a resolution-converted image from that of an original image, we use bifluency interpolation [3] using Fluency DA Function of Degree 2 [4] based on“ Fluency Information Theory ” [5]. Bifluency interpolation provides less staircase noise than bicubic interpolation. Through experiments, it is demonstrated that a moiré is not generated for an arbitrary magnification with our proposed method. And it is shown that our proposed method is superior in subjective image quality and computational time to conventional bicubic interpolation.

II. Resolution Conversion Method

A. Resolution Conversion Method Using Interpolating Function

Resolution conversion for a raster image is the process of increasing or decreasing pixels from an original image according to conversion magnification. At this time, we must determine unknown pixel values after resolution conversion. To determine them, the methods using interpolating functions have been conventionally used. Interpolation is the process of estimating the intermediate values of discrete samples.

It can be shown that a continuous signal can reconstructed by the use of an interpolating function, in one dimension, which has the form

$$L(t) = \sum_i L(i) \cdot h(t-i) \ . \tag{1}$$

Where $L(i)$ is the input pixel value being reconstructed, i is the coordinate of the input pixel, and $h(t)$ is the interpolating function and is considered as a kind of impulse responses. The interpolating function converts discrete data into continuous signal by an operation of linear combination and must be $h(0) = 1$ and $h(n) = 0$ when n is any nonzero integer.

Two-dimensional interpolation is easily accomplished by performing one-dimensional interpolation in each dimension as follows.

$$L(x,y)=\sum_i\sum_j L(i,j)\cdot\phi(x-i,y-j), \tag{2}$$

$$\phi(x,y)=h(x)\cdot h(y)\ , \tag{3}$$

where $\phi(x,y)$ is the two-dimensional interpolating function defined as the direct product of one-dimensional interpolating function $h(t)$.

There are some interpolating functions such as nearest-neighbor, bilinear, bicubic or Lanczos. Nearest-neighbor, bilinear and bicubic are used in Adobe Photoshop. Bicubic interpolation is most commonly used because of its smoothness.

B. Bifluency Interpolation

One of our research groups had established " Fluency Information Theory " which is a new information theory for flexible conversion between digital and analog signals. In this theory, one of the subspaces of L^2 (the space of square-integrable functions) is classified into subspaces by the times of continuous differentiability of the functions. We denote the function space as ${}^mS$, which is composed of piecewise polynomials of degree (m-1) with only (m-2) times continuous differentiability. The theory can be considered as both a generalization of Shannon's sampling theorem and that of wavelet theory.

Fluency DA Function of Degree 2,

$$ {}^3_{[c]}\psi(t)=\begin{cases} -\frac{t^2}{4\tau^2}-\frac{t}{\tau}-1, & -2\tau\le t<-\frac{3}{2}\tau\\ \frac{3t^2}{4\tau^2}+\frac{2t}{\tau}+\frac{5}{4}, & -\frac{3}{2}\tau\le t<-\tau\\ \frac{5t^2}{4\tau^2}+\frac{3t}{\tau}+\frac{7}{4}, & -\tau\le t<-\frac{\tau}{2}\\ -\frac{7t^2}{4\tau^2}+1, & -\frac{\tau}{2}\le t<\frac{\tau}{2}\\ \frac{5t^2}{4\tau^2}-\frac{3t}{\tau}+\frac{7}{4}, & \frac{\tau}{2}\le t<\tau\\ \frac{3t^2}{4\tau^2}-\frac{2t}{\tau}+\frac{5}{4}, & \tau\le t<\frac{3}{2}\tau\\ -\frac{t^2}{4\tau^2}+\frac{t}{\tau}-1, & \frac{3}{2}\tau\le t\le 2\tau\\ 0, & otherwise\ , \end{cases} \tag{4}$$

is one of sampling functions derived from the sampling function of $m = 3$ class signal space. Where τ means a sampling interval. For the remainder of this paper, τ is set to 1. Figure 1 shows the wave form of Fluency DA Function of Degree 2 and Fig.2 shows its amplitude characteristic. Since Fluency DA Function of Degree 2 converges to 0 at 2 point after and before the sampling point, no truncation error is provided in applications. Actually, this function is applied to digital-analog converter of CD player and DVD-Audio player known as " Fluency Audio ". Due to this function, Fluency Audio can generate supersonic component, which conventional sinc function cannot generate. Therefore Fluency Audio has won many awards.

The pixel values of resolution-converted image with bifluency interpolation are calculated according to the following procedure. First, convert the coordinate of interpolated image $(\tilde{i},\tilde{j})$ into that of the original image (x,y) based on the conversion magnification α as follows.

$$x=\frac{\tilde{i}}{\alpha},\ y=\frac{\tilde{j}}{\alpha}\ . \tag{5}$$

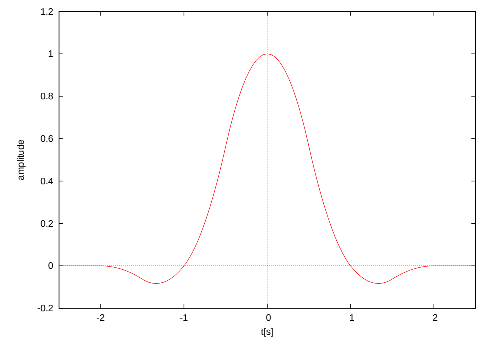


Fig. 1. Fluency DA Function of Degree 2 (sampling interval $\tau = 1$)

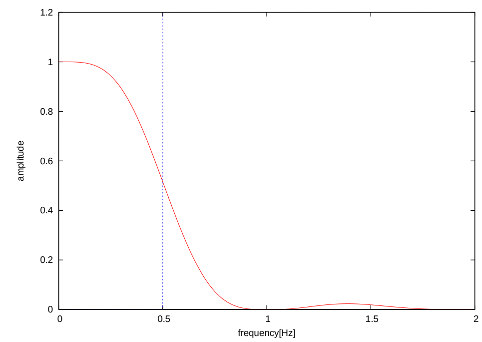


Fig. 2. Amplitude characteristic of Fluency DA Function of Degree 2 (Dashed line shows Nyquist frequency.)

Then, calculate the values of the resolution converted image $\tilde{L}(\tilde{i},\tilde{j})$ using two-dimensional Fluency DA function,

$$\psi(x,y)={}^3_{[c]}\psi(x)\cdot{}^3_{[c]}\psi(y)\ , \tag{6}$$

as the interpolating function as follows.

$$\tilde{L}(\tilde{i},\tilde{j})=\sum_{i=\lfloor x\rfloor-1}^{\lfloor x\rfloor+2}\sum_{j=\lfloor y\rfloor-1}^{\lfloor y\rfloor+2}L(i,j)\cdot\psi(x-i,y-j)\ , \tag{7}$$

where $\lfloor a\rfloor$ is the maximum integer which is not greater than a. As seen from Eqs.4 and 7, since Fluency DA Function of Degree 2 is compactly supported (outside the interval $(-2,2)$, the function is 0), bifluency interpolation does not provide any truncation errors and can decide an arbitrary pixel value of resolution-converted image by only $4\times 4 = 16$ points of an original image (Fig.3). This method provides less staircase noise than bicubic interpolation.

In the following sections, we describe the mechanism of generation of moiré and our proposed method according to the list of symbols Table I.

III. Generation of Moiré in Halftone Image

A. Basic Matters of Halftone

The halftone [6] is a pattern of dots to simulate continuous tone imagery by binary in the offset printing. The area ratio of a binary pattern is pseudo-perceived as continuous tone because of a human visual performance.

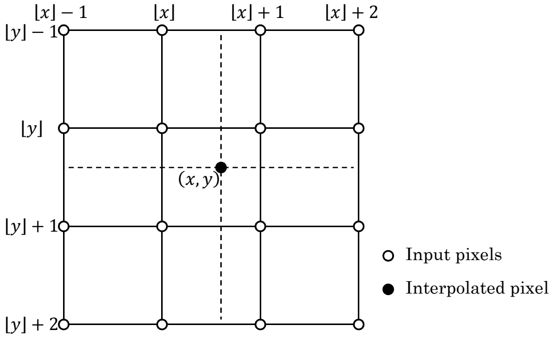


Fig. 3. Bifluency interpolation

The size of the input halftone image	$I \times J$ pixel
Pixel values of the input image	$L(i,j)$, $i = 0, 1, \cdots, I-1$, $j = 0, 1, \cdots, J-1$
The size of one cycle pattern of the input image	$P \times Q$ pixel
Pixel values of the one cycle pattern and one pixel before and after it of the input image	$H(p,q)$, $p = -1, 0, 1, \cdots, P$, $q = -1, 0, 1, \cdots, Q$
Conversion magnification	$\alpha = \frac{b}{a}$
The size of output (resolution-converted) image	$\lfloor \alpha I \rfloor \times \lfloor \alpha J \rfloor$ pixel
Pixel values of the output image	$\tilde{L}(\tilde{i}, \tilde{j})$, $\tilde{i} = 0, 1, \cdots, \lfloor \alpha I \rfloor - 1$, $\tilde{j} = 0, 1, \cdots, \lfloor \alpha J \rfloor - 1$
The size of one cycle pattern of the output image	$\lfloor \alpha P \rfloor \times \lfloor \alpha Q \rfloor$ pixel
Pixel values of one cycle pattern of the output image	$\tilde{H}(\tilde{p}, \tilde{q})$, $\tilde{p} = 0, 1, \cdots, \lfloor \alpha P \rfloor - 1$, $\tilde{q} = 0, 1, \cdots, \lfloor \alpha Q \rfloor - 1$
Fluency DA function of degree 2	${}^{3}_{[c]}\psi(t)$
Two-dimensional Fluency DA function	$\psi(x,y) = {}^{3}_{[c]}\psi(x) \cdot {}^{3}_{[c]}\psi(y)$

TABLE I
LIST OF SYMBOLS

The halftone is divided into two classes, AM (amplitude modulation) screen and FM (frequency modulation) screen. Former represents tone by changing area of dots, latter by changing the number of dots per unit area. The AM screen is commonly used to create comics.

The AM screen as a digital image can be considered to be composed of a periodic array of one size ($P \times Q$ pixel) images. An example of a halftone image and its one cycle pattern are shown in Fig. 4.

B. Mechanism of Generation of Moiré with Conventional Resolution Conversion

When resolution of a halftone image having periodicity is reduced with conventional method using interpolating functions, a moiré that is a pattern different from the original image might be generated. In this section, we describe the mechanism of generation of moiré.

The halftone image is composed of the periodic array of one cycle pattern. We assume the size of one cycle pattern

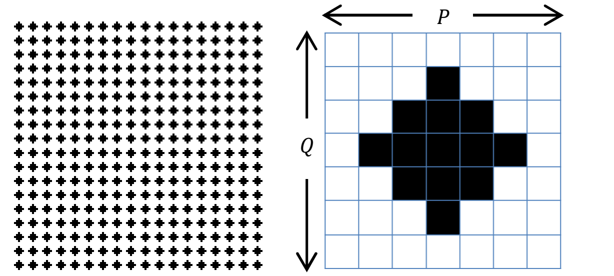


Fig. 4. Halftone image at left, and image of one cycle pattern of halftone image at right

of the halftone image to be $P \times Q$ pixel, and the reduction magnification to be $\alpha = \frac{b}{a}$. If both P and Q are integral multiples of a, since both αP and αQ can be integers, the $\alpha P \times \alpha Q$ pixel pattern is generated after resolution conversion. Therefore it corresponds to the original $P \times Q$ pixel pattern and a moiré cannot be generated. In contrast, if either P or Q is not an integral multiple of a, since either αP or αQ cannot be an integer, $\alpha P \times \alpha Q$ pixel pattern cannot be generated because coordinates of a pixel must be an integer. Therefore, the pattern different from the original image, that is a moiré, is generated after resolution conversion.

An example is shown in Fig.5. If a halftone image (a) composed of a pattern (c) (7×7 pixel) is reduced to half with bicubic interpolation, since $\alpha P = \alpha Q = \frac{7}{2}$ (not integers), the $\frac{7}{2} \times \frac{7}{2}$ pixel-pattern cannot be generated. Instead of that size pattern, the 7×7 pixel-pattern (d) which is four times bigger than it and includes four patterns of original image (c) is generated. Thus, resolution-converted image (b) having moiré is generated.

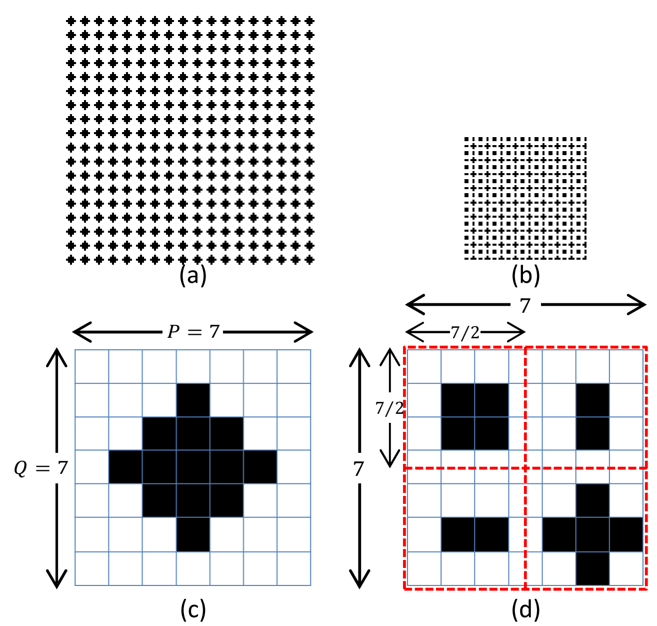


Fig. 5. (a) Original halftone image, (b) Reduced image with bicubic interpolation (Magnification is $\frac{1}{2}$ along each dimension.), (c) One cycle pattern of original image, (d) One cycle pattern of reduced image (Dashed lines show the areas corresponding to one cycle pattern of original image.)

IV. Resolution Conversion Method Preserving Periodic Structure of Halftone Using Bifluency Interpolation

When using conventional method, if either αP or αQ is not an integer, a pattern of $\alpha P \times \alpha Q$ pixel cannot be generated and a moiré is generated. Thus, we focus a halftone image which is composed of a periodic array of one cycle pattern. In our proposed method, we generate one cycle pattern of a resolution-converted image from that of an original halftone image, and generate a resolution-converted halftone image by arranging it periodically. When generating one cycle pattern of a resolution-converted image from that of an original image, we use bifluency interpolation that our research group has proposed. The steps of our proposed method are as follows.

Step 1: Cutting One Cycle Pattern Out of an Original Halftone Image

Cut one cycle pattern and one pixel before and after it along each dimension $(P+2) \times (Q+2)$ pixel from an original halftone image. That is, the pixel values of one cycle pattern of original image, $H(p,q)$ is set as follows.

$$\begin{aligned} &H(p,q) = L(p+P, q+Q), \\ &p = -1, 0, \cdots, P,\ q = -1, 0, \cdots, Q\ . \end{aligned} \tag{8}$$

Where the values of P and Q are given manually.

Step 2: Generation of One Cycle Pattern of a Resolution-Converted Image

Define the size of one cycle pattern after resolution conversion as $\lfloor \alpha P \rfloor \times \lfloor \alpha Q \rfloor$ pixel. Then generate that size image $\tilde{H}(\tilde{p}, \tilde{q})$ from the image cut out in step 1 with bifluency interpolation as the following procedure. First, convert the coordinate of the interpolated pixel $(\tilde{p}, \tilde{q})$ into (x, y) as follows.

$$x = \tilde{p} \cdot \frac{P}{\lfloor \alpha P \rfloor},\ y = \tilde{q} \cdot \frac{Q}{\lfloor \alpha Q \rfloor}\ . \tag{9}$$

Then calculate $\tilde{H}(\tilde{p}, \tilde{q})$ as follows.

$$\begin{aligned} &\tilde{H}(\tilde{p}, \tilde{q}) = \sum_{p=\lfloor x \rfloor -1}^{\lfloor x \rfloor +2} \sum_{q=\lfloor y \rfloor -1}^{\lfloor y \rfloor +2} H(p,q) \cdot \psi(x-p, y-q)\,, \\ &\tilde{p} = 0, 1, \cdots, \lfloor \alpha P \rfloor - 1,\ \tilde{q} = 0, 1, \cdots, \lfloor \alpha Q \rfloor - 1\ . \end{aligned} \tag{10}$$

The reason why we cut out not only one cycle pattern but also one pixel before and after the pattern at step 1 is that Fluency DA Function of Degree 2 converges to 0 at 2 point after and before the sampling point, thus a value of an arbitrary coordinate of a signal interpolated with this function is affected by 2 sampling points after and before the coordinate.

Step 3: Composition of a Resolution-Converted Image

Regard the image generated in step 2 as one cycle pattern of a resolution-converted image. Then compose a resolution-converted image by arranging the pattern periodically. That is, the output pixel values $\tilde{L}(\tilde{i}, \tilde{j})$ are decided as follows.

$$\begin{aligned} &\tilde{L}(\tilde{i}, \tilde{j}) = \tilde{H}(\tilde{i} \bmod \lfloor \alpha P \rfloor, \tilde{j} \bmod \lfloor \alpha Q \rfloor), \\ &\quad \tilde{i} = 0, 1, \cdots, \lfloor \alpha I \rfloor - 1, \tilde{j} = 0, 1, \cdots, \lfloor \alpha J \rfloor - 1\ . \end{aligned} \tag{11}$$

Where $a \bmod b$ means the remainder on division of a by b.

V. Experiments

A. Experimental Condition

We converted two images Fig.6 (200×200 pixel, binary) with our proposed method and bicubic interpolation. The size of one cycle pattern of the image-1 is 7×7 pixel and that of the image-2 is 12×12 pixel. Conversion magnifications are 500%, 80%, 60% and 40% along each dimension. We implement these algorithms with Microsoft Visual C++ 2008 and execute on the environment with Intel Core2 Duo E8400 CPU, 998MB RAM.

B. Experimental Results

Figures 7 and 9 show result images with our proposed method. Figures 8 and 10 show result images with bicubic interpolation. A moiré is not generated in any conversion magnification for each image with our proposed method. In contrast, a moiré is generated in magnification 80%, 60% and 40% for both images with bicubic interpolation. Especially a moiré stands out in magnification 40%. Our proposed method is superior in subjective image quality to bicubic interpolation.

Table II shows the comparison of computational time between our proposed method and bicubic interpolation. The computational time of our proposed method is about 2%-16% compared to that of bicubic interpolation. The reason why our proposed method is faster than bicubic interpolation is that the former converts only one cycle pattern of a halftone image, in contrast, the latter converts the entire halftone image.

Image-1

conversion magnification	500%	80%	60%	40%
proposed	49.9	3.3	1.6	2.9
bicubic	2068.4	59.7	61.8	18.1

Image-2

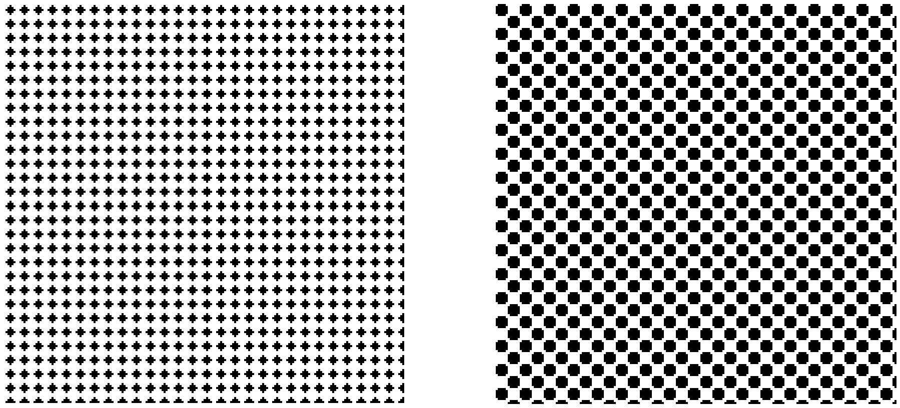
conversion magnification	500%	80%	60%	40%
proposed	66.9	2.6	1.9	2.2
bicubic	2051.7	107.3	37.8	18.1

TABLE II

Comparison of computational time (msec)

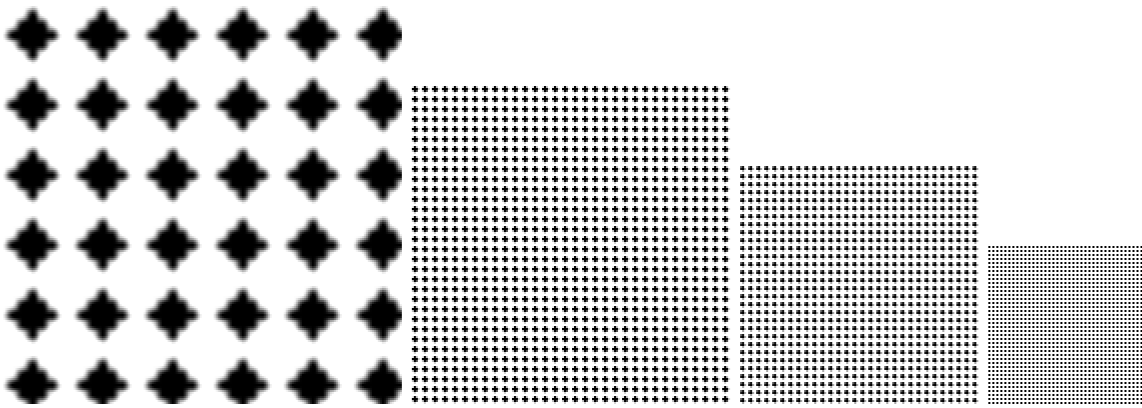
C. Application Example

Our proposed method can be applied to resolution conversion for the comic image which has the halftone region. Figure 11 shows an application example. (a) is the original comic image. (b) is the reduced image, where the halftone region with our proposed method and the line drawing region with bifluency interpolation. At this time, we assumed that the halftone region and line drawing region were already known. (c) is the reduced image with bicubic interpolation. Since, in image (b), any moirés are not generated, it is superior in subjective image quality to image (c).



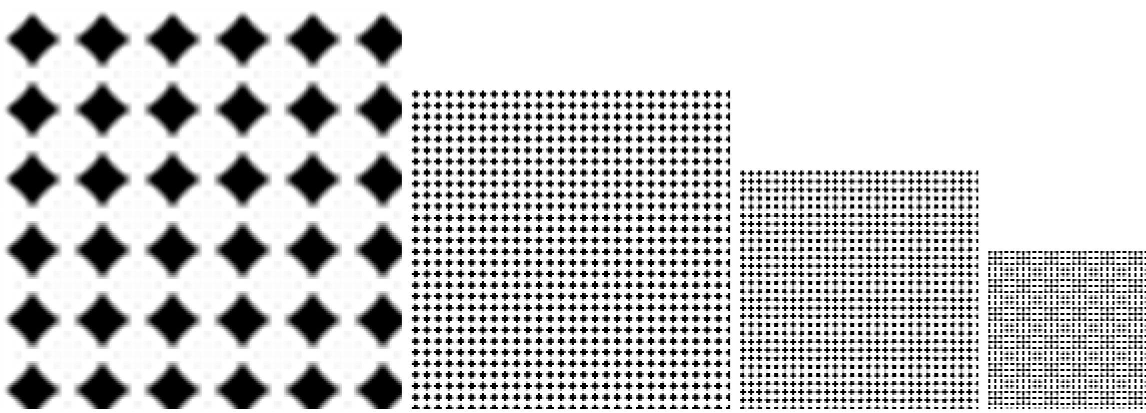
(a) Original image-1 (100%) (b) Original image-2 (100%)

Fig. 6. Original image-1 at left, original image-2 at right



500% (A portion of the converted image) 80% 60% 40%

Fig. 7. Resolution-converted images of image-1 with our proposed method (magnification: from left to right 500%, 80%, 60% and 40%)



500% (A portion of the converted image) 80% 60% 40%

Fig. 8. Resolution-converted images of image-1 with bicubic interpolation (magnification: from left to right 500%, 80%, 60% and 40%)

VI. Conclusion

In this paper, we proposed a high-quality resolution conversion method for halftone image which does not cause generation of moiré. Conventional resolution conversion methods using interpolating functions cause generation of moiré that leads to deterioration in quality. In our proposed method, we generate one cycle pattern of a resolution-converted image from that of an original halftone image and compose a resolution-converted image by arranging it periodically. Through experiments, it is shown that our proposed method is superior to bicubic interpolation because our proposed method does not generate a moiré and computational time of our proposed method is faster than that of bicubic interpolation.

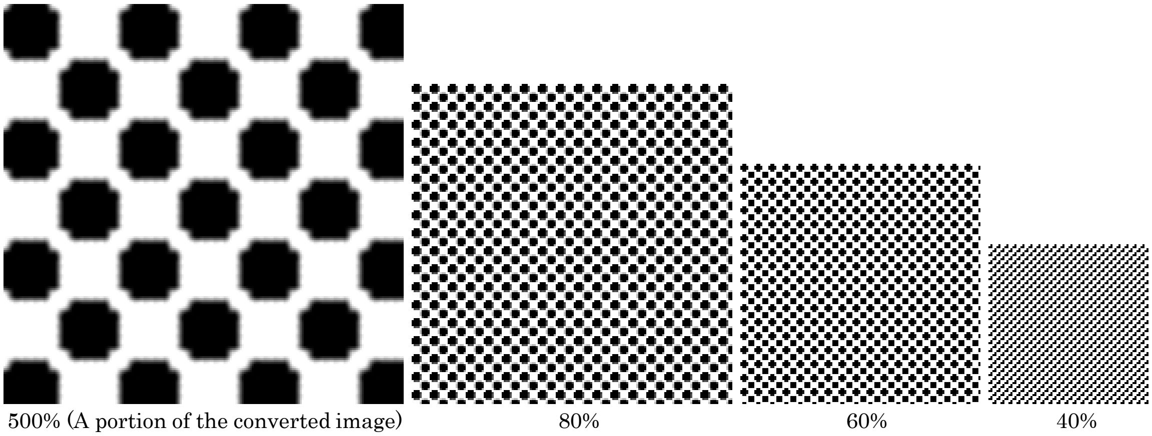


Fig. 9. Resolution-converted images of image-2 with our proposed method (magnification: from left to right 500%, 80%, 60% and 40%)

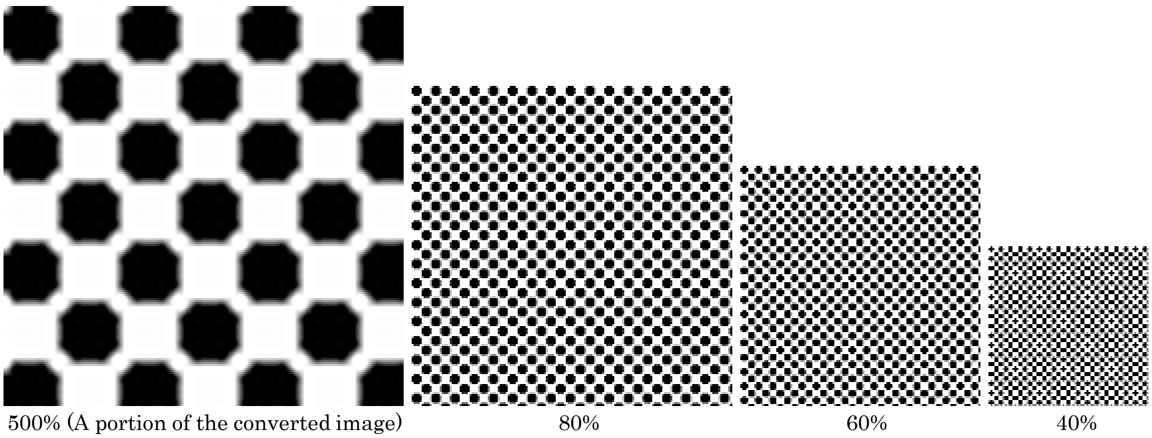


Fig. 10. Resolution-converted images of image-2 with bicubic interpolation (magnification: from left to right 500%, 80%, 60% and 40%)

Furthermore, this method can be applied to resolution conversion for the comic image.

Our proposed method targets only a halftone image whose density is uniform. Our future work is considering how to apply this method to a halftone image whose density is not uniform.

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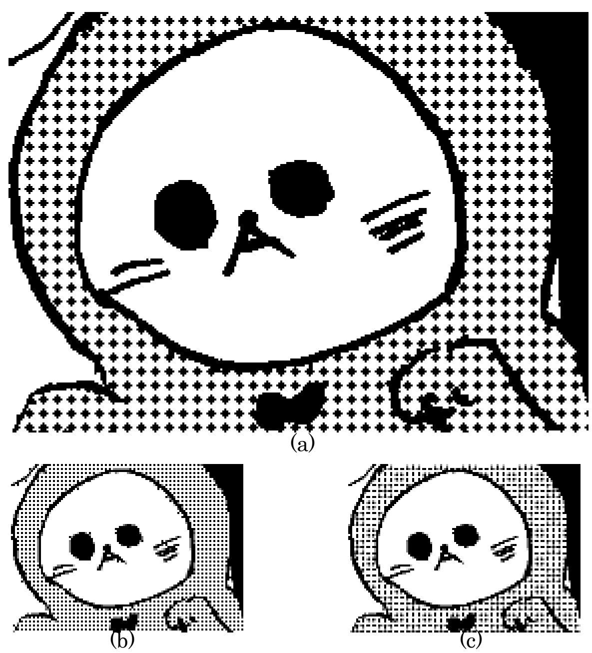

Fig. 11. (a) Original comic image, (b) Reduced image, where the halftone region is reduced with proposed method and the line drawing region with bifluency interpolation, (c) Reduced image with bicubic interpolation